InnoTech ALBERTA
A SUBSIDIARY OF ALBERTA INNOVATES

Towards Circularity in Alberta Plastic Waste Management: A White Paper on Current Recycling Practices, Emerging Innovations and Technology Gaps

Final Report

Prepared by
Karen Budwill, PhD
TriDung Ngo, PhD
Ataullah Khan Mohammed, PhD
InnoTech Alberta Inc.

Prepared for
Mehr Nikoo
Sr. Manager, Clean Technology
Alberta Innovates

Contract No. **C2022000765**

Date: March 17, 2023

Revisions: May 5, 2023, May 17, 2024

NOTICES OF REPORTS

1. This Report was prepared as an account of work conducted at INNOTECH ALBERTA INC. ("InnoTech") on behalf of Alberta Innovates. All reasonable efforts were made to ensure that the work conforms to accepted scientific, engineering and environmental practices, but InnoTech makes no other representation and gives no other warranty with respect to the reliability, accuracy, validity or fitness of the information, analysis and conclusions contained in this Report. Any and all implied or statutory warranties of merchantability or fitness for any purpose are expressly excluded. Alberta Innovates acknowledges that any use or interpretation of the information, analysis or conclusions contained in this Report is at its own risk. Reference herein to any specified commercial product, process or service by trade-name, trademark, manufacturer or otherwise does not constitute or imply an endorsement or recommendation by InnoTech.

2. Pursuant to the terms of the **C2022000765** Agreement dated Aug 30, 2022, any confidential and proprietary information contained in this Report is owned solely by Alberta Innovates. InnoTech confirms that Alberta Innovates is entitled to make such additional copies of this Report as Alberta Innovates may require, but all such copies shall be copies of the entire Report. Alberta Innovates shall not make copies of any extracts of this Report without the prior written consent of InnoTech. InnoTech further confirms that Alberta Innovates is entitled to distribute copies of this Report only to employees, agents and contractors of Alberta Innovates under terms that prohibit any further copying or distribution of the Report.

3. Any authorized copy of this Report distributed to a third party shall include an acknowledgement that the Report was prepared by InnoTech and shall give appropriate credit to InnoTech and the authors of the Report.

EXECUTIVE SUMMARY

Plastic waste, and in particular single-use plastic waste, has become a global crisis of concern in the 21st century. The intrinsic durability and convenience associated with the use of single-use plastics is driving its production, consumption and at the same time is overburdening the waste management sector. The bulk of single use plastics are non-recyclable under the current recycling systems and non-biodegradable in nature and end up at the landfill or as litter in the environment causing land and water pollution. As per the United Nations Environment Programme (UNEP) estimates, 6.9 of the 9.2 billion metric tonnes (Bt) manufactured plastics have ended up at the landfill since their early introduction in 1950s. According to Environment Canada, an average approximately 3 million metric tonnes (Mt) of plastic is discarded and sent to landfills in Canada every year, of which only about 9-10% is recycled.

To address the growing plastic waste crisis both on land and in water, the Canadian Council of Ministers of the Environment (CCME) launched a Zero Plastic Waste Strategy across Canada in late 2018. The strategy outlines a circular approach to tackle plastic waste and provides a time-bound framework for the implementation of a plastic circular economy in Canada. This plan sets out tangible actions and clear timelines to better prevent, reduce, reuse, recover, capture, and clean up plastic waste and pollution in Canada, with a goal of zero-plastic waste by 2030. On the Alberta front, the latest legislative amendment to Bill 83 under the Environmental Protection and Enhancement Amendment Act, enables the creation of an Extended Producer Responsibility (EPR) framework to transfer the responsibility of plastic waste generated back to the producer and manufacturers and free municipal waste management services from having to bear the costs. The EPR framework also includes accountability for tracing and tracking of plastics from manufacture to their end of life. It is believed it will foster changes at the producer level to reduce plastic usage and encourage the use of smarter packaging design (i.e., following the “Golden Design Rules” put forth by Canada Plastics Pact), and the use of alternative bio-degradable and bio-compostable polymers. Furthermore, in 2020, the Government of Alberta laid out a plan for enhancing plastic recycling in Alberta in their “Getting Alberta Back to Work: Natural Gas Vision and Strategy” document. It outlines a goal of establishing Alberta as Western North American’s centre of excellence for plastics diversion and recycling by 2030 focusing on advanced chemical and renewable, low-carbon plastics recycling research and deployment. The plan includes developing province-wide plastics recycling and diversion systems as well as coordinating across jurisdictions to divert plastics for advanced recycling so that critical economies of scale are achieved. A key part of the Alberta’s Natural Gas Vision and Strategy is to fully implement a plastics circular economy for economic prosperity and environmental sustainability. The plastics circular economy approach, with support from the EPR framework, will ensure investment in technological enhancement to recycling processes, and sustainable growth in not only new plastics but also value-added products from recycled plastics.

Considering the ongoing legislative and regulatory changes, shifts in societal perception, and technological advancements, Alberta Innovates’ Clean Resources approached InnoTech Alberta to conduct a scan of current waste management and recycling practices and ongoing technological innovations in plastic recycling and circular economy. The objectives of this white paper were to identify key technology gaps in plastic recycling in the whole plastic value chain (cradle-to-grave) and provide potential recommendations for supporting innovative technologies to not only enhance plastics recycling but to also develop a plastics circular economy. The outcomes of the technology gap analyses are broadly summarized below.

Technology Challenges and Gaps in Recycling: Mechanical recycling is currently one of the most mature and widely deployed approaches for recycling plastics, however it is characterized with degrading resin quality and cross contamination issues. Innovations in mechanical recycling approaches include the integration of advanced cleaning (e.g., using supercritical CO_2 to decontaminate plastics) and sorting modules into a conventional mechanical sorting train. Based on the facility design, it would include pre-sorting, shredding, washing, drying, enhanced optical sorting, deodorization, and extrusion-pelleting. There are several waste sorting and segregation facilities in Alberta that use conventional mechanical recycling technology, however use of advanced mechanical recycling is still in its infancy. Continued development of innovative pre-treatment or post-treatment technologies that can seamlessly integrate into existing mechanical recycling facilities and that increase material retention and quality while reducing environmental impacts are needed. Tracers such as fluorescent pigments incorporated into the plastic substrate can aid in the pre-sorting step. BASF's reciChain™ program is being scaled up to a pre-commercial level in Alberta and marks an advancement in plastic waste management that would support the effective tracking and sorting of plastics.

There are novel recycling processes (both mechanical and chemical) that are being developed that can recycle mixed plastic waste together thus eliminating the need for pre-sorting. The Canadian company Plastonix is, according to their website, able to recycle mixed plastic waste by fusing them together into an intermediate product that can then be converted to processable chips or powdered material.

Chemical recycling (often called advanced recycling by industry) involves the use of chemical solvents and/or thermo-chemical and/or mechano-chemical approaches to depolymerize the polymeric unit into monomeric units or into platform chemical for upcycling opportunities. Chemical recycling enables recycling of a wider range of waste plastics than that of traditional mechanical recycling. However, the biggest challenge of chemical recycling versus mechanical recycling is the cost as it is typically capital intensive and operationally complex and associated with the use and/or generation of hazardous and toxic chemicals. There are several types of chemical recycling processes including pyrolysis, solvolysis, catalysis and gasification. This review focused mainly on innovations in solvolysis (solvent-based processes) and catalysis (both chemical and biological) processes.

Innovations in solvolysis processes include the use of supercritical fluids and eutectic solvents to depolymerize plastics. These processes, however, are energy-intensive and thus the development of solvents that can dissolve polymers at low temperatures to minimize heat requirements and have low-boiling points to enable energy-efficient recovery by distillation are required. The use of microwave heating is an alternative process to solvolysis and pyrolysis. Indeed, microwave-based recycling is being developed for commercial scale by the Canadian company, Pyrowave-Canada.

Innovations in catalytic recycling center around processes with low activation energy and high product specificity. Novel chemical catalysts are being developed to depolymerize a wide range of plastics with built-in tolerance for various inhibitory additives. Processes using biological catalysts are relatively passive with low energy intensity; however, they currently lack the ability to handle mixed plastic streams. New prospecting methods using computational approaches have enabled the rapid discovery, optimization, and industrial use of enzymes and engineered microbes for degradation of a range of different plastics and plastics-derived intermediates. Indeed, ongoing research and innovation in the optimization of (bio)catalysts (i.e., range of plastics, mixed plastics, reaction rates) and the enhanced recovery of depolymerized products from the reaction vessels are required.

Innovations in Recycling Difficult-to-Recycle Plastics and Polymers:

Several thermoplastics and most of thermoset plastics are currently very difficult to recycle. Amongst the thermoplastics, Polyvinyl Chloride (PVC), Polystyrene (PS), and polyamides (e.g., Nylon) are known as difficult-to-recycle thermoplastics due to the presence of additives (stabilizers, colorants, or plasticizers), inherent bulkiness and toxicity thus impeding the recovery of high-quality recycled material. Innovations in either mechanical or chemical processes are required to enhance the recyclability of these thermoplastics. For example, Polystyvert, based in Montreal, has developed a process that uses an essential oil solvent to dissolve PS. The company claims on their website that the essential oil is very safe and can be easily reused to recycle more material.

Innovations in thermoset plastics and materials recycling processes are required that are environmentally friendly and financially beneficial for producers and waste management organizations. The most important classical thermosets that are recyclable are polyurethanes, epoxies, and silicones, since either valuable material can be recovered, or the output material can be used as building blocks in the manufacturing process of the original plastic material. Currently, recycling of thermoset waste is mainly limited to grinding and combustion. However, thermoset materials can successfully be degraded through thermal treatment at different temperatures, by catalysis, irradiation with or without the presence of water, and solvolysis. A recent innovation in enhancing the recyclability of thermoset polyurethanes is converting the permanently cross-linked thermosets into vitrimer polymers without depolymerization in a process called vitrimization. Vitrimers consist of molecular covalent networks which can change their topology by thermally activated bond-exchange reactions. Research has shown that the vitrimized thermosets exhibited comparable mechanical properties and solvent resistance with the original thermoset polymers with the added benefit of being recyclable.

Technology Gaps in Material Design to Enhance Recyclability

Intelligent design with a full cradle-to-cradle life cycle analyses is essential for promoting circularity in the waste plastic sector. Eliminating or reducing use of dyes, coloring agents, binding additives and non-polymeric substances during design phase will simplify separation and facilitate recyclability of different plastic types. Producing packaging consisting of only one type of polymer (i.e., mono-material packaging) will also aid in more efficient recycling. By considering these issues at the design stage, it becomes easier to disassemble products into waste fractions that do not contain residues of other material. These design considerations have been included in the “Golden Design Rules” published by the Canada Plastics Pact that aim to increase progress towards using less and better plastic.

The production of 100 % polyolefin plastics and composites without additives can be achieved with multisite polymerization catalysts and specialized injection-molding processes, such as oscillating packing injection molding. Research and development of new processes to produce mono-material plastic film for food packaging that still retains the attractive properties of being low cost, light weight, tough and impervious to oxygen and moisture are being conducted.

Other innovative research in material design to enhance recyclability is the production of polymers with tunable degradation properties, i.e., polymers that degrade under pre-determined conditions into their monomers or oligomers. An example is silyl ether-based cyclic olefins that were copolymerized with norbornene derivatives to produce copolymers with varying stability when exposed to hydrochloric acid. Research into the incorporation of polymers with enzymes that have triggered intrinsic self-biodegradation properties is also being conducted. This ongoing research is testing how enzymes incorporated in the adhesives or in tie layer polymers can facilitate rapid and effective separation of multiple plastic layers. There is an ongoing need for innovation and optimization of designed-for-recycling-plastic so that they not only function as intended but that they also integrate seamlessly into existing recycling facilities or into novel upcycling processes.

Technology Innovations in Upcycling

Chemical and biological recycling technologies can break down plastics into its building blocks and transform them into valuable secondary raw materials. These materials can then be used to produce new chemicals and plastics. An Example of upcycling of polymers into more valuable materials is the synthesis of fiber-reinforced plastics, via combination of depolymerized Polyethylene Terephthalate (PET) with renewably sourced, bio-derived olefinic acids. End-of-life Nylon-12 and Nylon-6 has been treated with supercritical CH_3OH to produce methyl ω-hydroxydodecanoate, a fatty acid ester derivative with potential antimicrobial agent applications with yields of 85%. The selective conversion of High-Density Polyethylene (HDPE) wastes to a few well-defined products, namely, succinic, glutaric, and adipic acid through microwave assisted acidic hydrolysis has also been developed.

Microbial catalysis can funnel plastics-derived intermediates into central metabolism to produce value-added chemicals in a process called bio-upcycling. Research is also occurring in the upcycling of mixed plastic waste through tandem chemical oxidation and bioconversion. In general, gaps around process optimizations to ensure upcycling technologies are cost-effective, marketable and have minimal environmental impacts need to be addressed.

The technology gap review showed that there is no one technology that will handle all plastic waste at once. In fact, one must look at the broader picture of plastic waste management, from waste collection, sorting, upcycling to plastic re-design and replacement in order to determine the best plastic waste treatment process or processes for building a sustainable plastic circular economy.

Recommendations for supporting innovative research and development in plastic waste recycling and circularity therefore include:

1. Supporting the digitalization of plastic waste management such as manufacturing polymers with unique barcodes or incorporation of specific fluorescent dyes to facilitate source separation and segregation and to incentivize recyclability at their end of lifetime.
2. Enhancing the automation of waste management by developing and optimizing the accuracy of optical sensors and robotic sorters.
3. Addressing technological gaps in processes that demonstrate substantive ability to tackle mixed heterogenous plastics into new products, thus minimizing (or eliminating) the need for extensive sorting and segregation equipment.
4. Continued research and development as well as scaling up of novel mechanical, chemical and biological (separate or in combination) processes that provide improved recycling and material retention rates while mitigating environmental impacts such as energy use, greenhouse gas emissions and release of hazardous chemicals or harmful effluents.
5. Developing new polymer chemistries for packaging (particularly for flexible packaging and multilayer materials) that are recyclable by design. New materials may require certain functional properties and product performance matching or exceeding the conventional plastics., which would constitute a major domain for applied research and development.
6. Developing new upcycling technologies to further enhance the value of plastic wastes. Upcycling options improve plastic waste recycling economics and promote in the establishment of plastic circular economy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Towards Circularity in Alberta Plastic Waste Management: A White Paper on Current Practices, Emerging Innovations and Technology Gaps

Karen Budwill, PhD
TriDung Ngo, PhD
Ataullah Khan Mohammed, PhD

1.0 INTRODUCTION

Plastics are materials consisting of any of a wide range of synthetic or semi-synthetic organic compounds that are malleable and can be molded into solid objects. Plastics are most commonly derived from petrochemicals; however, a number of various plastics are made from renewable materials such as polylactic acid derived from corn or cellulosics. Most of the petroleum- and natural gas liquid-based plastic types in use today entered large-scale production around the middle of the 20th century. Due to their low cost of production, ease of manufacture, versatility, low weight, durability and imperviousness to water, plastics are used in a multitude of products of different scale and for a variety of civil and industrial applications (Andrady and Neal, 2009; Wei and Zimmermann, 2017). In many areas, they have substituted natural materials such as wood, paper, and glass in most of their former uses (Andrady and Neal, 2009). As a result, plastics have become omnipresent in our daily life. After having fulfilled its intended purpose, which is often a short first-use cycle, a plastic item is supposed to follow either of three pre-determined paths: recycling, incineration, or permanent disposal in landfills as shown in Figure 1.

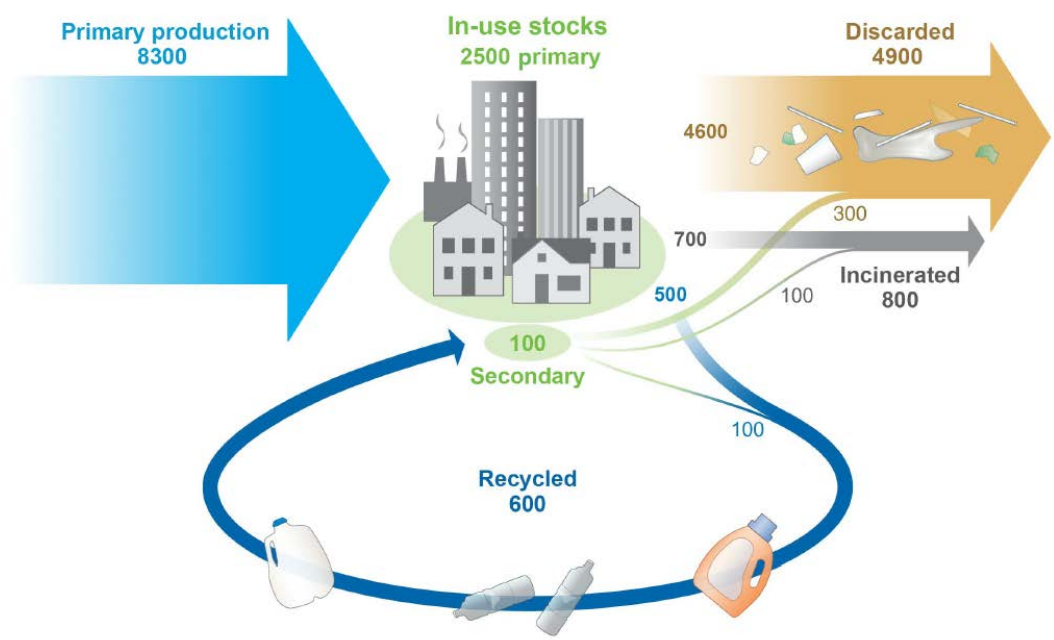


Figure 1. Global production, use, and fate of polymer resins, synthetic fibers, and additives (1950 to 2015; in million metric tons). From Geyer et al., 2017.

The bulk of single use plastics are non-recyclable and non-biodegradable in nature and end up at the landfill or as litter in the environment causing land and water pollution. As per the United Nations Environment Programme (UNEP) estimates, 6.9 of the 9.2 billion metric tonnes (Bt) manufactured plastics have ended up at the landfill since their early introduction in 1950s[1]. According to Environment Canada, an average approximate 3 million metric tonnes (Mt) of plastics are discarded and sent to landfills in Canada every year, of which about 9-10 % are recycled.

To address the growing plastic waste crisis both on land and in water, the Canadian Council of Ministers of the Environment (CCME) launched a Zero Plastic Waste Strategy across Canada in late 2018[2]. The strategy outlines a circular approach to tackle plastic waste and provides a time-bound framework for implementation in Canada. This plan sets out tangible actions and clear timelines to better prevent, reduce, reuse, recover, capture, and clean up plastic waste and pollution in Canada, with a goal of zero-plastic waste by 2030.

At the provincial level, Alberta's Extended Producer Responsibility (EPR) regulation came into force on November 30, 2022[3]. The aim of the regulation is to transfer the responsibility of plastic waste generated back to the producer and manufacturers and free the municipal waste management services from having to bear the costs. It is believed the EPR framework will foster changes at the producer level to reduce plastic usage, to trace and track plastics from manufacturing to end of life, and to encourage the use of alternative bio-degradable and bio-compostable polymers. The Alberta Recycling Management Authority[4] (ARMA) will provide oversight of Alberta's new PPP (Packaging and Paper Products) EPR system. The first major deadline for producers is to present their collection and management plans to ARMA by April 1, 2024. It should be noted that the EPR framework does not yet include PPP from the industrial, commercial, and institutional sectors.

Furthermore, in 2020, the Government of Alberta laid out a plan for enhancing plastic recycling in Alberta in their "Getting Alberta Back to Work: Natural Gas Vision and Strategy" document[5] and as depicted in Figure 2. It outlines a goal of establishing Alberta as Western North America's centre of excellence for plastics diversion and recycling by 2030, with a focus on advanced chemical and renewable, low-carbon plastics recycling research and deployment. The plan includes developing Province-wide plastics recycling and diversion systems in place as well as coordinating across jurisdictions to divert plastics for advanced recycling so that critical economies of scale are achieved. Among several recommendations is the exploration of partnership opportunities with recycling associations, municipalities, plastics associations, academia, and industry to advance plastics diversion and recycling research and development, innovation, and technology deployment. In addition to recycling, organic plastics or bioplastics that are truly biodegradable can provide another solution to the burgeoning plastic waste problem. There are, however,

[1] https://www.unenvironment.org/resources/report/single-use-plastics-roadmap-sustainability
[2] CCME – Canadian Council of Ministers of the Environment (2018) Strategy on plastic waste. PN1583.
[3] https://www.alberta.ca/regulated-extended-producer-responsibility-programs.aspx
[4] https://www.albertarecycling.ca/
[5] https://www.alberta.ca/natural-gas-vision-and-strategy.aspx

still challenges around cost-effectiveness and meeting product design demands which requires further research and development.

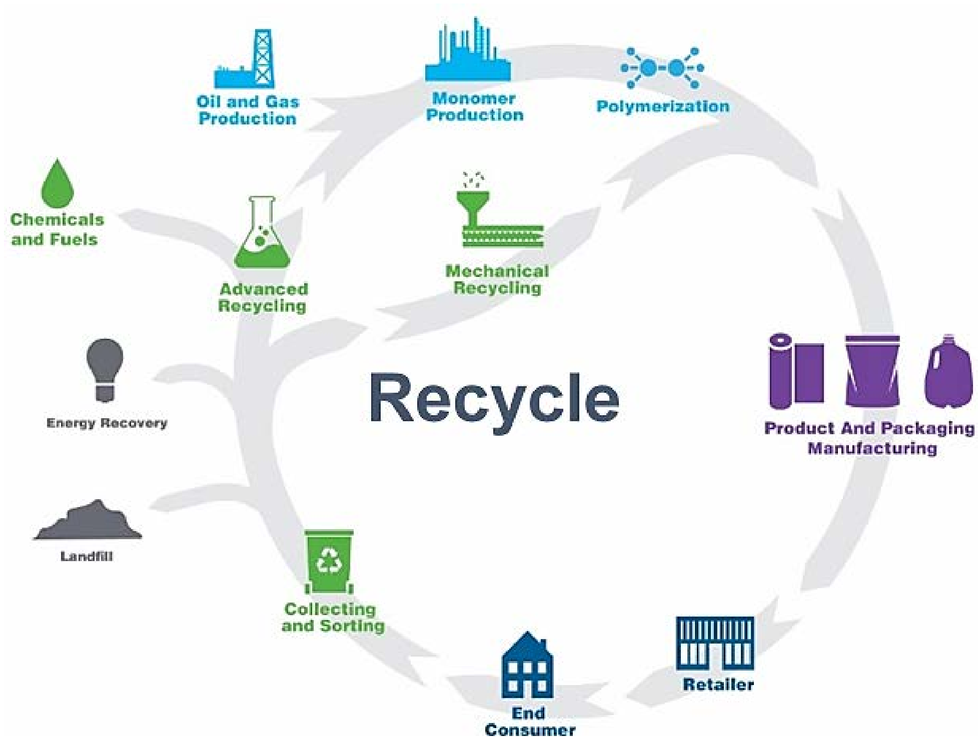


Figure 2. Plastics value chain and opportunities[6].

The objectives of this Alberta Innovates-commissioned study were to identify key recycling technology gaps and provide well informed recommendations for the inception of a sustainable plastic circular economy in the province of Alberta. This review compliments the research being conducted by Alberta Energy and Alberta Environment and Protected Areas (AEPA) on plastic feedstock characterization (types and volumes) and biopolymer production in Alberta. Together, these reviews will aid in the development of a provincial plastic circular economy strategy. The outcomes of this review are designed to align with Government of Canada's Zero plastic waste[7] strategic and with Government of Alberta's the natural gas strategy[8].

[6] https://plasticsalliancealberta.ca/plastics-facts/

[7] https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste.html

[8] https://www.alberta.ca/natural-gas-vision-and-strategy.aspx

2.0 METHODOLOGY

For this technology gap review, detailed searches through publicly available reports, news items, conference proceedings and electronic journals were completed to find literature related to the themes of plastic recycling. General search terms were used encompassing iterative search strategies to capture a broad swath of literature. Once collected, abstracts were reviewed to determine whether the documents met the inclusion criteria.

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.

3.0 BACKGROUND INFORMATION ON PLASTICS AND PLASTICS RECYCLING

3.1 Plastic Types and Recyclabilities

Petroleum and naturel gas liquid-based plastics can be categorized as being either thermoplastics or thermoset plastics. Thermoplastics are plastics that can be heated, cooled, and reshaped repeatedly (e.g., polystyrene and polyethylene), while thermosets are plastics that can only be shaped once because their polymerization creates a three-dimensional network that cannot be remelted or solubilized (e.g., unsaturated-polyester, vinyl ester, epoxy, and polyurethanes). Several plastic type categories i.e., class 1 to 7 based on their Resin Identification Code, RIC (Figure 3), can be correlated to their known recyclability and degradability as detailed in the following sections.

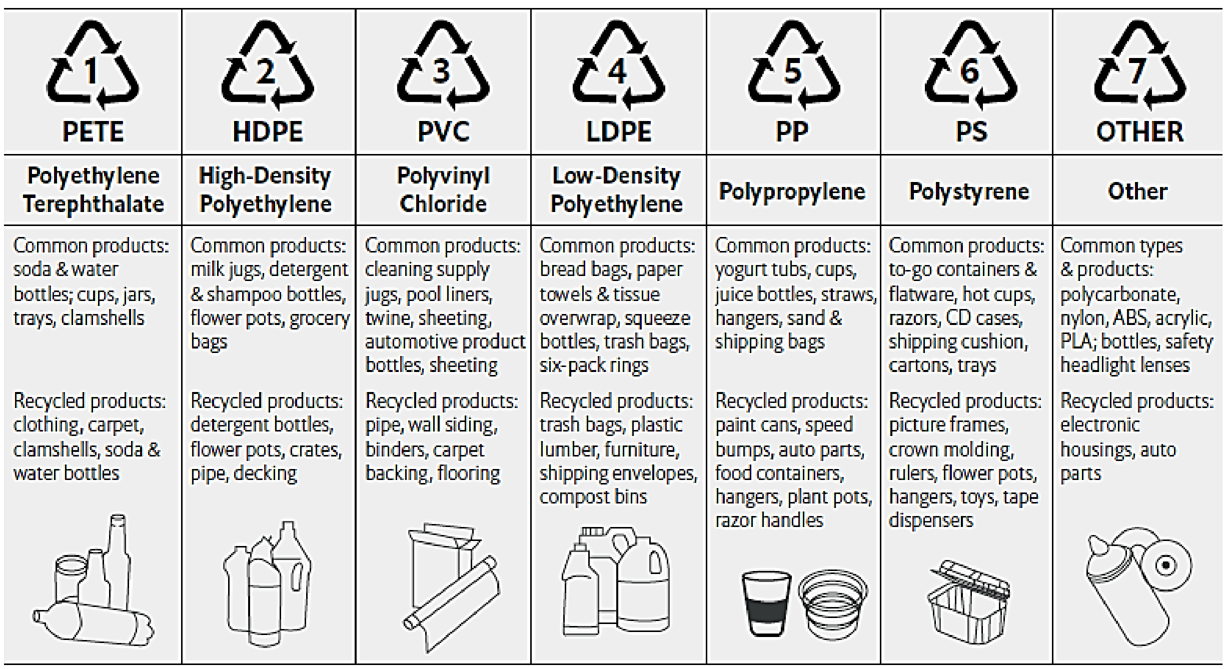


Figure 3. Plastic resin Identification Codes: their common uses and recycled products (The Economist Group, 2021).

Some characteristics of plastics that make them recalcitrant to recycling (Ellis et al., 2021) include:

- Presence of additives and polymers (metals, dyes, pigments, fillers, antioxidants, and plasticizers).
- Chemical additive content (antioxidants, flame retardants or other fillers) could inhibit specific catalyst systems.
- Degree of crystallinity.

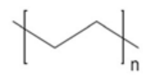
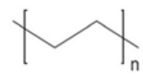
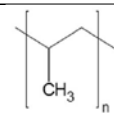
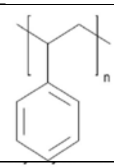
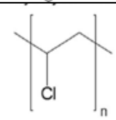
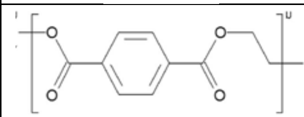
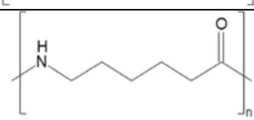
- Presence of covalent bonds which are typically not accessible for depolymerization by biological or abiotic means (e.g., polyethylene and polypropylene exhibit only aliphatic C-H and s*p*^{3} C-C bonds that are difficult to cleave).

3.1.1 Thermoplastic Types and Recyclabilities

Any plastic that melts into a soft, pliable form at a certain temperature and then solidifies upon cooling is a thermoplastic. These materials can be re-melted and recycled and are typically stored as pellets before the molding process. Common thermoplastics include nylon, polyester, polyethylene, polypropylene, polystyrene, and polyethylene terephthalate (PET). They find use in a wide range of industries and products from clothes and cookware to carpets and packaging.

There are 6 main types of thermoplastics that make up to over 92% of all plastics ever made (Geyer at al., 2017). These can be classified into two groups based on their chemical structure: those having a C-C backbone and those having a heteroatomic backbone. Table 1 provides an overview of thermoplastics, including their structure, uses and ease of recycling.

Table 1. Types and characteristics of thermoplastics.

Group	Thermoplastic	Abbreviation	Structure	Production[a] (Mt/year)	Uses	Ease of Recycling[b]	% of Global Waste[b]
C-C Backbone	High Density Polyethylene	HDPE		47	Detergent and bleach bottles, snack boxes, milk jugs, toys, buckets, trash bins.	Easy	14%
	Low Density Polyethylene[c]	LDPE		58	Packaging film, shopping bags, bubble wrap, flexible bottles, wire and cable insulation.	Manageable	20%
	Polypropylene	PP		62	Bottle tops, drinking straws, insulated coolers, fabric and carpet fiber, diapers.	Manageable	19%
	Polystyrene	PS		22.7	Plastic-foam cups, egg boxes, meat trays, packing peanuts, insulation, toys.	Difficult	6%
	Polyvinyl Chloride	PVC		34.5	Credit cards, pipes and fittings, window and doorframes, synthetic leather.	Very Difficult	5%
Heteroatomic Backbone	Polyethylene terephthalate	PET		30	Beverage bottles, food jars, clothing and carpet fibers, some shampoo bottles	Easy	11%
	Polyamides (e.g. Nylon-6)	PA		n.a.	Industrial yarn, textile, plastic film, molded parts for cars, electrical equipment.	Very Difficult	24%

[a]Beckman, 2018.
[b]Parker, 2018.
[c]The data cited is for LDPE as a whole and could not be broken down further into liner (LLDPE), medium (MDPE), crosslinked (XPLE) polyethylene analogues.

In 2020, the global volume of thermoplastics produced was estimated at 400 Mt[9]. Up to 68% of PET, which was estimated at almost 30 Mt produced in the same year[10], is recycled, corresponding to 30% of all recycled thermoplastics.

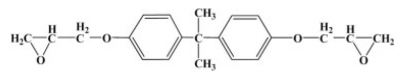
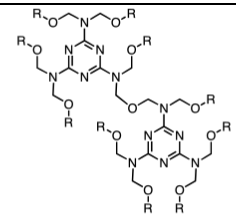
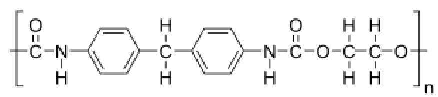
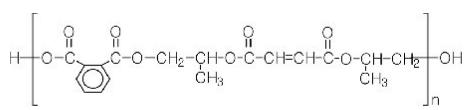
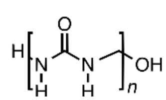
3.1.2 Thermoset Types and Recyclabilities

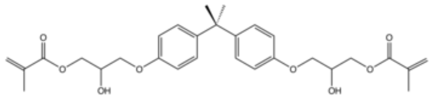
Thermoset materials and their composites are characterized by a long-life cycle with their main applications in aircrafts, wind turbines, sport equipment and construction as insulating materials. Thermosets are classified into polyester resins, epoxy resins, vinyl ester resins, phenolic, polyurethane, and other high temperature resins such as cyanate esters. The global volume of thermosets produced in 2020 was approximately 42 Mt, while the most recycled thermoset, polyurethane, had no more than 20% of its worldwide production of 10 Mt being recycled.

Table 2 provides an overview of the thermosets, including their structure, uses and ease of recycling.

[9] https://www.statista.com/statistics/1192886/thermoplastics-production-volume-by-type-globally/
[10] https://www.marketsandmarkets.com/Market-Reports/recycled-pte-market-248965407.html

Table 2. Types and characteristics of thermosets.

Thermosets	Abbreviation	Structure	Production (Mt/year)	Uses	Ease of Recycling
Epoxy	EP		3.2[a]	Coatings, flooring, concrete restoration, crack repair, and as joint material for tiles, automotive & transportation, aerospace, sport equipment.	Very Difficult
Melamine Formaldehyde	MF		0.0011[b]	Plywood and particleboard adhesives, laminated countertops and tabletops, dishwasher-safe tableware, and automotive surface coatings.	Very Difficult
Polyurethane (Flexible, Rigid, Rubber)	PU		22.4[c]	Flexible and rigid foams, durable elastomers and high-performance adhesives and sealants, fibers, seals, gaskets, condoms, carpet underlayment, and hard plastic parts, high-resilience foam seating, rigid foam insulation panels, surface coatings and sealants, synthetic fibers.	Very Difficult
Unsaturated Polyester	UPE		6.8[d]	Composite materials. Wood paints. Flat laminated panels, corrugated panels, ribbed panels. Gel coat for boats, automotive and bathroom fixtures. Colouring pastes, fillers, stucco, putties and chemical anchorings. Self-extinguishing composite materials.	Very Difficult
Urea Formaldehyde	UF		28.5[e]	Laminates, textiles, paper, wrinkle-resistant fabrics, cotton blends, and foam artificial snow. It can also be found as a coating for electrical appliances such as desk lamps.	Very Difficult

Thermosets	Abbreviation	Structure	Production (Mt/year)	Uses	Ease of Recycling
Vinyl Ester	VE		0.71[f]	It is a common resin in the marine industry, FRP tanks and vessels. Vinyl resins are often used in repair materials and laminating.	Very Difficult

[a] https://www.chemanalyst.com/industry-report/epoxy-resin-market-597
[b] https://www.mordorintelligence.com/industry-reports/melamine-formaldehyde-market#:~:text=The%20melamine%20formaldehyde%20market%20reached,in%20various%20end%2Duser%20industries
[c] https://www.statista.com/statistics/720341/global-polyurethane-market-size-forecast/#:~:text=The%20global%20market%20volume%20of,million%20metric%20tons%20in%202021.
[d] https://www.revex.co.in/2021/12/16/importance-of-unsaturated-polyester-resin/
[e] https://www.researchandmarkets.com/reports/338593/formaldehyde_global_strategic_business_report
[f] https://www.chemanalyst.com/industry-report/vinyl-ester-resin-ver-market-661

3.2 Plastic Recycling Terms

As can be seen in Table 3, the terminologies and definitions used in the context of plastics recycling varies greatly.

Table 3. Comparison of plastics recycling and recovery terminology (Adapted from Hopewell et al., 2009).

Plastics Industry Terms	ASTM D5033 Definitions	ISO 15270 Definitions
Mechanical Recycling: • Closed-loop recycling	Primary recycling	Mechanical recycling
Mechanical Recycling: • Open-loop recycling • Downgrading • Downcycling	Secondary recycling	
Purification Recycling (Dissolution) and Molecular Decomposition (Depolymerization)	Tertiary recycling	Chemical recycling
Advanced Recycling		
Conversion: • Valorization • Pyrolysis • Gasification	Quaternary recycling	Energy recovery

To avoid any confusion and misunderstandings for this report, the terminologies adopted by the ISO (International Organization for Standardization) standards as indicated in Tables 3 and 4 were used (the exceptions were for down cycling, open loop recycling and upcycling, Table 4, as indicated).

A glossary of plastic recycling terms is presented in Table 4.

Table 4. Plastic recycling glossary.

Term	Definition	Source
Advanced Recycling	Used interchangeably with chemical recycling (refer to chemical recycling)	ISO 15270:2008 ACS Advanced Recycling (americanchemistry.com)
Biological Recycling	Aerobic (composting) or anaerobic (digestion) treatment of biodegradable plastics waste under controlled conditions using micro-organisms to produce, in the presence of oxygen, stabilized organic residues, carbon dioxide and water or, in the absence of oxygen, stabilized organic residues, methane, carbon dioxide and water.	ISO 15270:2008
Chemical recycling	The conversion to monomer or production of new raw materials by changing the chemical structure of plastic waste through cracking, gasification or depolymerization, excluding energy recovery and incineration.	ISO 15270:2008
Closed loop recycling	Closed-loop systems are developed so that all of the materials in manufactured goods can be recycled, usually for use in the same type of product. For closed-loop recycling, the manufacturing process is usually designed with recycling in mind.	ISO 14001

Term	Definition	Source
	Closed loop system in which packaging is reused by a company or a co-operating group of companies.	ISO 18603:2013
Depolymerization	Chemical reversion of a polymer to its monomer(s) or to a polymer of lower relative molecular mass	ISO 472:1999
Down cycling	Downcycling involves creating low value products from higher value waste streams. Open-loop recycling operations results in downcycling or reprocessing of mixed plastic waste streams, which were generally higher in value in their previous use.	sustainabilitydictionary.com
Energy recovery	Production of useful energy through direct and controlled combustion. Energy recovery in the form of heat, steam, or electricity generation using plastics waste as substitutes for primary fossil fuel resources.	ISO 15270:2008
Mechanical recycling	Processing of plastics waste into secondary raw material or products without significantly changing the chemical structure of the material.	ISO 15270:2008
Municipal solid waste (MSW)	MSW, waste from households, offices, hotels, malls, trade premises, schools, institutions, food and beverage premises, markets and municipal services, such as street cleaning and maintenance of recreational areas, which municipalities take care of.	ISO 24161:2022
Open loop recycling	Open-loop recycling is any recycling process where the recycled materials are converted into both new raw materials with another waste by-product.	https://www.generalkinematics.com/blog/open-loop-vs-closed-loop-recycling/ https://www.aaapolymer.com/quick-guide-to-open-loop-vs-closed-loop-recycling/
	Open-loop system in which packaging is reused amongst unspecified companies.	ISO 18603:2013
Plastic waste	Discarded material which contains as an essential ingredient a high polymer.	ISO 472:2013, 2.702
Recyclable	Waste that can be recovered and processed into material for the manufacture of a new product	ISO 472:2013, 2.702
Recycling	Reprocessing, by means of a manufacturing process, of a used plastic or packaging material into a product, a component incorporated into a product, or a secondary (recycled) raw material, excluding energy recovery and the use of the product as a fuel.	ISO 15270:2008
Re-use	Use of a product more than once in its original form.	ISO 15270:2008
Upcycling	The transformation of plastic waste into value-added products.	Balu et al. (2022)

3.3 OVERVIEW OF RECYCLING PROCESSES

3.3.1 Mechanical Recycling

Mechanical recycling of plastics refers to the processing of plastics waste into secondary raw material or products without significantly changing the chemical structure of the material. Current mechanical recycling processes are depicted in Figure 4:

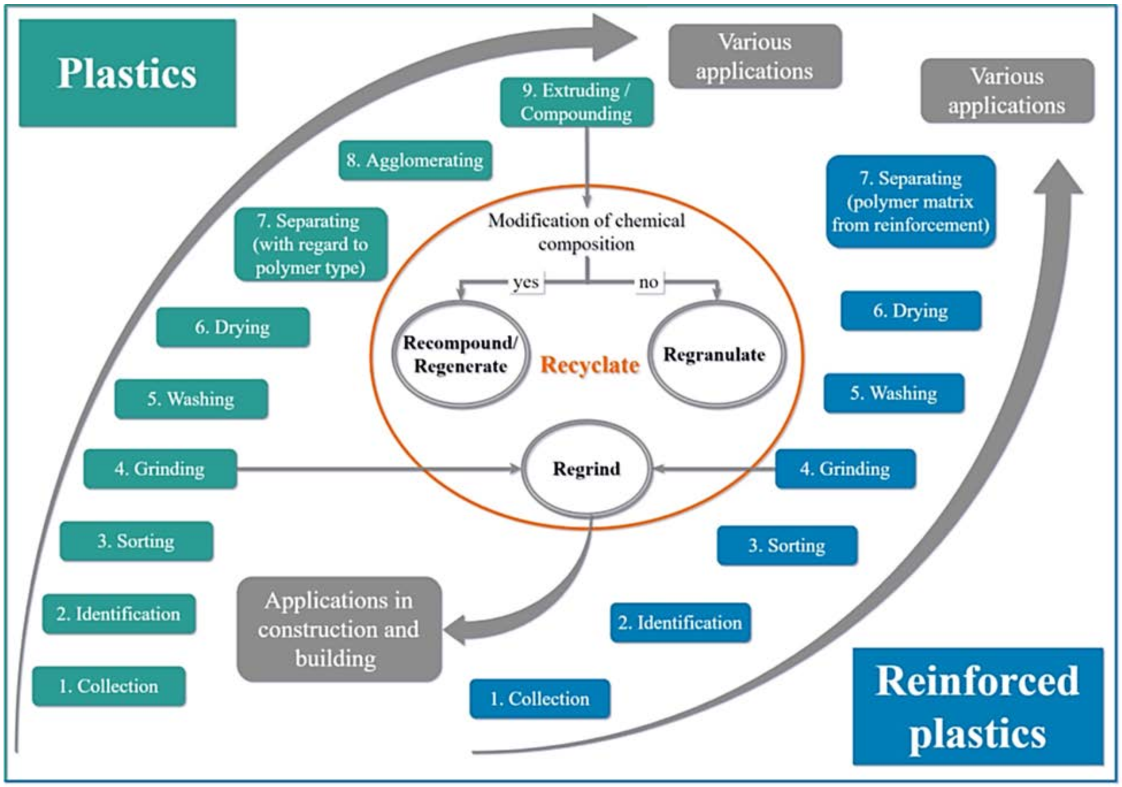


Figure 4. Major steps of mechanical recycling (Shamsuyeva and Endres, 2021).

Before recycling, most plastics are sorted either by their resin identification code (Figure 3) or by various sorting systems to identify the resin, ranging from manual sorting and picking of plastic materials to mechanized automation processes that involve shredding, sieving, separation by rates of density using air, liquid, or magnetics, and complex spectrophotometric distribution technologies such as ultraviolet/visible light, near-infrared spectroscopy, and laser. Some plastic products are also separated by color before they are recycled. After sorting, the plastic recyclables are then shredded. These shredded fragments then undergo processes to eliminate impurities like paper labels. This material is melted and often extruded into the form of pellets which are then used to manufacture other products. The highest quality purification may be referred to as “regenerate” as shown in Figure 4.

The major advantage of mechanical recycling is its universal applicability to all recycling pathways and ease of implementation to either decentralized or centralized waste collection operations. Mechanical recycling plants are simple and inexpensive and have a relatively low demand on energy and resources compared with plants required for chemical recycling. Currently, optimization of the above-mentioned processing steps enables partial improvement of the output material (plastic recyclate) properties like smell, purity, and color. The major disadvantage of mechanical recycling is the need for pure plastic waste streams, as the quality of the plastic recyclates is strongly dependent on the quality and purity of the input-stream (plastic waste).

3.3.2 Chemical Recycling

Chemical recycling involves the use of a chemical solvent or thermochemical process or combinations thereof to reclaim the monomeric units from plastic waste, or to convert it into other platform chemicals. During chemical recycling the polymers are depolymerized or converted under controlled conditions and the recovered chemical constituents are used as a feedstock for production of new materials. Chemical recycling is currently used for recycling of post-consumer PET, PE, and PP, although it has great potential for hard to recycle plastics such as thermosets and composite materials.

Several advantages of chemical over mechanical recycling include:

- Generation of new value-added raw materials (such as lactic acid) while the initial material properties are preserved.
- Avoiding material degradation or deterioration as seen with mechanical recycling. Thus, the material value is retained within the plastic economy indefinitely.

However, there are several disadvantages to chemical recycling including (The Economist Group, 2021):

- High CAPEX/OPEX costs.
- High complexity, relatively energy-intensive and potential for high CO_2 emissions.
- Use and generation of hazardous and toxic chemicals and solvents.
- A large volume of plastic feedstock is required to keep chemical recycling plants operating and sustainable.
- Variability in chemical reactivity to different plastics as well as the complexity of conducting chemical depolymerization on solid feedstocks.

Despite the disadvantages, chemical recycling is being seen as a viable alternative or addition to mechanical recycling especially for difficult to recycle plastics (Ellis et al., 2021). There are numerous chemical processes under development as outlined in Table 5. Table 6 summarizes and compares the main advantages and disadvantages of chemical and mechanical recycling.

Table 5. Summary of emerging chemical recycling technologies (The Economist Group, 2021).

Technical Process	Description
Chemolysis or Solvolysis	Use of a chemical agent such as methanol, glycol or just water to break down plastic material into its monomers
Non-catalytic thermal pyrolysis	Thermal decomposition of waste in the absence of oxygen to produce a plastic oil
Catalytic pyrolysis	Thermal decomposition of waste in the absence of oxygen but in the presence of a catalyst to enhance yield, operating window and other performance metrics.
Plasma pyrolysis	A process integrating conventional pyrolysis with thermochemical properties to transform plastic waste into synthetic gas very quickly.
Hydrothermal recycling	Uses water at elevated pressures and temperatures to cut longer-chain hydrocarbon bonds in plastics to produce oils and chemicals that can be reprocessed to make virgin monomers and then into plastics.
Gasification	A process which takes place in a gasifier, generally in a high-temperature or high-pressure vessel, where controlled or limited oxygen and/or steam are in directed contact with the feed material to produce synthesis gas that can be chemically converted into monomers.

Table 6. Advantages and disadvantages of mechanical versus chemical recycling.

Property	Mechanical Recycling	Chemical Recycling
Technical requirements for infrastructure / processes	Low	High
Requirement on quality for input stream	High	Low – Medium
Quality of output material	Depends on the quality of input material. Moderate quality improvement using process parameters and additives is possible, but it is inversely proportional to the technical expense	Very high
Cost	Low	High
Possibility of decentralized processing	Possible	Currently technically challenging and uneconomic
Environmental impacts (e.g., chemical wastes, byproducts, GHGs)	Low to Medium	High

3.3.3 Biological Recycling

In biological recycling, biocatalysts (enzymes and microbes) are used to depolymerize or deconstruct the plastic resin or polymer. A biological recycling process using biocatalysts resulting in up-cycled products generally follows three steps: 1) production of the depolymerization enzyme (i.e., catalyst), 2) deconstruction of the polymer, and 3) conversion of the plastic hydrolysate to the final product. Conducting the depolymerization and conversion steps in separate tanks is the most common approach currently.

Many physicochemical properties of plastics can affect their biodegradability including whether they are hydrolysable or non-hydrolysable. Polymers with hydrolysable chemical bonds in their backbone such as

PET (Webb et al., 2013) and PUR (Cregut et al., 2013) are thought to be more susceptible to biodegradation than PE, PS, PP and PVC (Zheng et al., 2005; Tokiwa et al., 2009). The highly stable carbon-carbon (C-C) bonds of non-hydrolysable plastics must be pre-oxidized first to achieve depolymerization (Zheng et al., 2005; Restrepo-Florez et al., 2014).

Biological recycling is an emerging technology and presents several benefits over chemical recycling processes including:

- Lower/modest exothermic processes, therefore biocatalysts offer the potential to contribute to energy-efficient polymer deconstruction and upcycling (Ellis et al., 2021).
- No harsh conditions such as high temperatures or toxic chemicals are required for biodegradation (Verschoor et al., 2022).
- Costs for bulk enzyme production can be relatively low.
- Allows for the retrieval of monomers which can be polymerized into new plastics or upcycled into new compounds.

However, there are several technological challenges and disadvantages of biological recycling over chemical recycling including:

- Lower tolerances to severe processing conditions compared to chemical catalysts and sensitivity to changes in temperatures, ionic strengths, pH, or solvents which can cause enzyme denaturation and loss of activity.
- The presence of additives such as hydrophobic plastic depolymerization products (styrene, octane, and octanol) can be toxic as they perturb microbial membranes (Ellis, et al., 2021).
- Handling of combinations of different plastics is challenging since no enzyme is expected to be active on all plastics (Verschoor et al., 2022).
- Recalcitrance of high crystallinity regions in plastics to enzymatic degradation (Nikolaivits et al., 2021).

4.0 CURRENT STATE OF PLASTIC PRODUCTION, MANAGEMENT, AND MARKET POTENTIAL FOR RECYCLED PLASTICS IN CANADA AND ALBERTA.

In this section, the current state of plastic production and waste management in Canada and Alberta is characterized along with the market potential for recycled plastics.

4.1 PLASTIC PRODUCTION IN CANADA AND ALBERTA

Although Canadians make up less than 0.5% of the global population, Canada use 1.4% of all plastics produced[11]. With total sales estimated at CA$35 billion, plastic resin (CA$10 billion) and plastic product (CA$25 billion) manufacturing in Canada accounts for over 5% of the sales in the Canadian manufacturing sector and employs 93,000 people across 1,932 establishments (Green 2021).

Global demand and production of plastics is growing. In Canada, plastic products are in demand in most sectors of the economy, with approximately 4,667 kilotonnes (Kt) of plastics introduced to the domestic market on an annual basis (more than 125 kg per capita). Packaging, construction, and automotive sectors show a particular demand for plastic, accounting for 69% of plastic end-use. Figure 5 shows the Canadian plastics market revenue share by end-use industry[12].

[11] https://oceana.ca/en/reports
[12] https://publications.gc.ca/

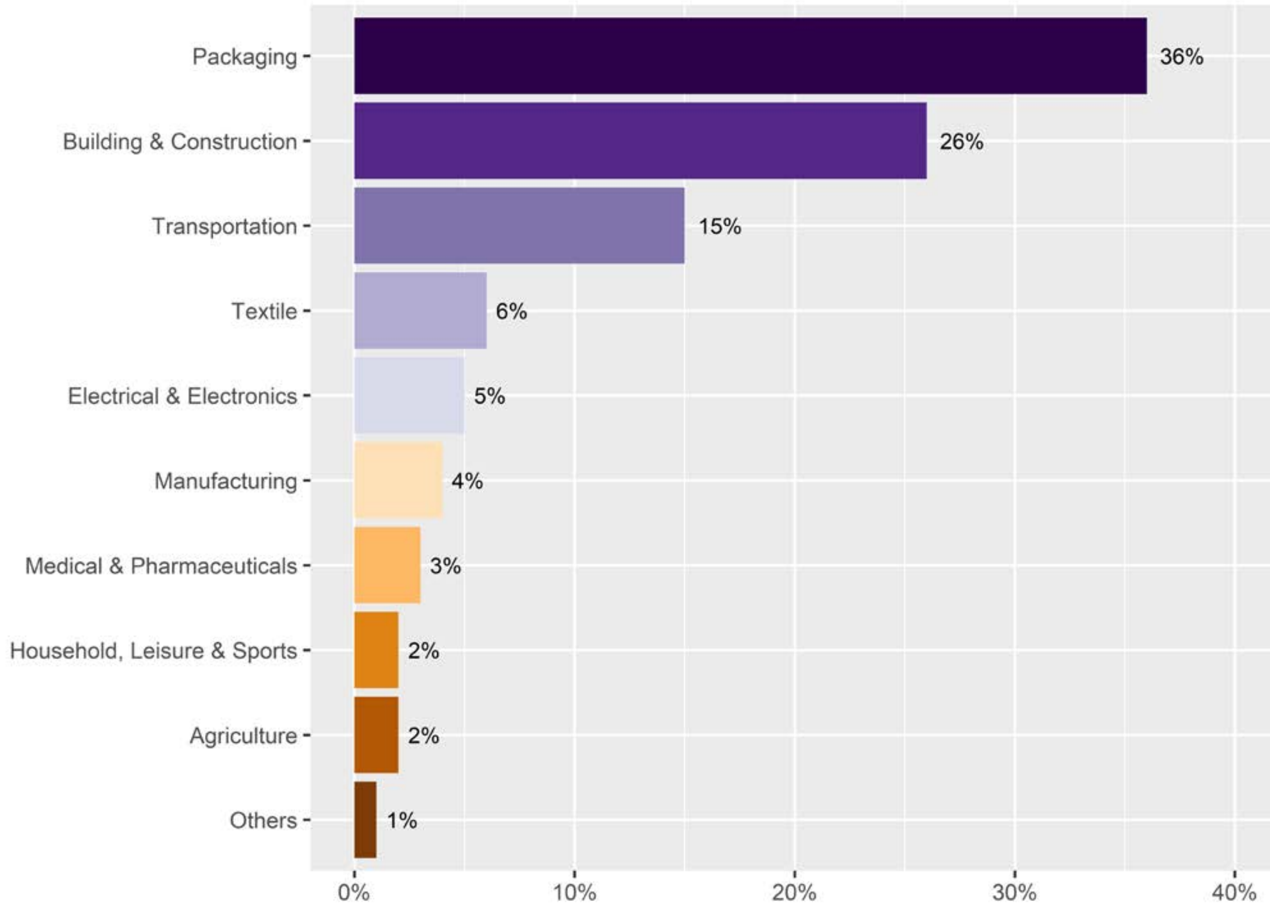


Figure 5. Canada plastics market revenue share, by end-use industry, 2021 (%)[13].

The Canadian petrochemical sector uses refined petroleum and natural gas liquids (NGLs) to manufacture a range of petrochemicals such as benzene, butadiene/butane, butylene, cumene, ethylene, isobutene/isoprene, propylene, and styrene. These petrochemicals are used in a wide variety of industrial applications and as inputs in the manufacturing process of other products including plastics and polymers.

Olefins (a class of chemicals that include ethylene, propylene, and 1,3-butadiene) are produced primarily via steam cracking (ethylene cracking) of chemicals commonly found in NGLs such as ethane, propane, butanes, and pentanes. Olefins can also be produced during the crude oil (naphtha) refining process yielding primarily propylene with limited ethylene (in contrast, steam cracking of NGLs yield ethylene primarily, with other olefins in minority). Thus, the primary petrochemical facilities in Canada include steam crackers (olefins) and refineries (aromatics) that produce plastic resins or its derivatives such as different grades of polyethylene, polypropylene, and 6 polystyrene. These derivatives are then used to produce end-use manufactured products such as plastic bags and films, fibres, and solvents[14].

[13] https://www.industryarc.com/Report/19562/canada-plastics-market.html

[14] https://natural-resources.canada.ca/sites/www.nrcan.gc.ca/files/energy/energy-resources/CERI_Study_153_Full_Report.pdf

Most of the plastic production in Canada is concentrated in Alberta (Joffre and Ft. Saskatchewan), Ontario (Sarnia-St. Clair), and Québec (East Montreal). Both Alberta and Ontario generate their plastic precursors from NGLs in the following ratios and yields (Green, 2021):

- Alberta - 92% olefins (4097 kt/y) and 8% aromatics (370 kt/y)
- Ontario - 60% olefins (1139 kt/y) and 40% aromatics (762 kt/y)

Alberta is thus a major supplier of NGL-derived olefins while Ontario has a more balanced inventory of both olefins and aromatics for the plastic resin manufacturing sector.

Alberta's chemistry and plastics industry was valued at $16.2 billion and employed about 23,000 people directly and indirectly in 2019[15]. In 2015, Alberta's plastic resins and plastic products industry generated a total revenue of $6.3 billion, with $4.7 billion coming from plastic resins and remainder of $1.6 billion came from plastic manufactured products[16].

Alberta's NGLs, condensed from natural gas, contain ethane and propane, which are used for making ethylene and propylene starting materials. Alberta is also a significant supplier of ethane as a petrochemical feedstock to manufacture plastics and other industrial and consumer materials. Alberta's four ethane-cracking plants have a capacity of 4.1 Mt per year accounting for almost 80% of Canada's total installed ethylene-producing capacity. These plants make plastics and other building block chemicals from natural gas liquids. The Canada Energy Regulator forecasts an excess ethane supply, which can be tapped to build additional steam cracking capacity in Alberta.

Alberta's Industrial Heartland (AIH) is home to largest concentration of petroleum refineries and chemical processing plants in Canada covering 582 km^2 located northeast of Edmonton, Alberta. Some of the major petrochemical operations in this area include the Shell Scotford upgrader and manufacturing facility in Strathcona County, and the Plains Midstream fractionation and storage facility in the City of Fort Saskatchewan. The Shell Scotford manufacturing facility cracks bitumen to produce various chemicals, including propane, styrene monomer (i.e., primary ingredient in hard plastics) and ethylene glycol (i.e., primary ingredient in the production of soft plastics, polyester fabric, and antifreeze). The other major player, the Plains Midstream fractionation facility produces ethane and propane from its NGLs. Some of the other major players in the petrochemical sector of the Alberta's Industrial Heartland include Dow Chemical Canada, Pembina, and Heartland Polymer. Table 7 highlights the key petrochemical companies operating in the plastic resin sector in Alberta.

[15] https://plasticsalliancealberta.ca/plastics-facts/

[16] https://open.alberta.ca/dataset/5a2a552d-bc90-4c24-85ee-33cc4d6bd550/resource/a90865b7-2c62-458e-ad37-86cbca190ddc/download/sp-commentary-01-30-17.pdf

Table 7. Key Alberta petrochemical companies operating in the plastic resin sector[17].

Company	Details
NOVA Chemicals https://www.novachem.com/olefins/ Joffre, Alberta, Canada	One of the largest ethylene and polyethylene production complexes in the world, the Joffre site consists of five manufacturing facilities.
DOW Chemicals https://ca.dow.com/en-ca.html Fort Saskatchewan, Alberta	Dow operates ethylene cracker units at Fort Saskatchewan and has recently proposed Path2Zero expansion project to pioneer world's first net-zero integrated ethylene cracker.
Plains Midstream https://www.plainsmidstream.com/ Fort Saskatchewan, Alberta	Plains Midstream fractionation facility brings in and treats NGLs which are then dispersed to petrochemical facilities as feedstock.
Shell Scotford Chemicals Scotford | Shell Canada Strathcona County, Alberta	The Scotford chemicals facility can produce up to 450 Kt of styrene monomer and ethylene glycol a year. The other products from the facility include aromatics, lower olefins, and intermediates.
Pembina https://www.pembina.com/operations/partnerships/pembina-gas-infrastructure/ Fort Saskatchewan	Pembina Gas Infrastructure (PGI) is a premier gas processing entity in Western Canada with a combined capacity of 141 million m^3 per day. It operates throughout the Montney and Duvernay trends from central Alberta to northeast British Columbia.
Heartland Polymer https://heartlandpolymers.com/ Strathcona County, Alberta	Heartland Polymers is the global brand representing Inter Pipeline's petrochemical business unit covering the production of polypropylene pellets. Currently supplying approximately 500,000 metric tonnes/yr, representing 5% of the North American polypropylene market.

4.2 CURRENT STATE OF PLASTIC WASTE GENERATION AND MANAGEMENT IN CANADA

4.2.1 Waste Generation

Most of the information accessible in the space was derived from the Environment Canada's National Waste Characterization Report[18]. As per 2016 estimates, 34 Mt of municipal solid waste (MSW) were collected at landfills, about a quarter of which (9 Mt) was diverted through organic residual management and material recovery operations (MRF) and the remainder of MSW was landfilled or incinerated for energy recovery.

Figure 6 shows the current national average of materials (as a percentage) in residual MSW originating from residential; industrial, commercial, and institutional (ICI); and demolition, land-clearing, and construction (DLC) sources. Bio-degradable waste makes up the bulk of the MSW inventory categorized into food, diapers, paper, cardboard, wood, and yard/garden waste. Plastics and construction demolition waste make up the remainder of the waste inventory. Plastic waste makes up just over 13% of residential MSW and approximately 25% of ICI MSW.

[17] https://investalberta.ca/petrochemicals/
[18] National Waste Characterization Report (publications.gc.ca)

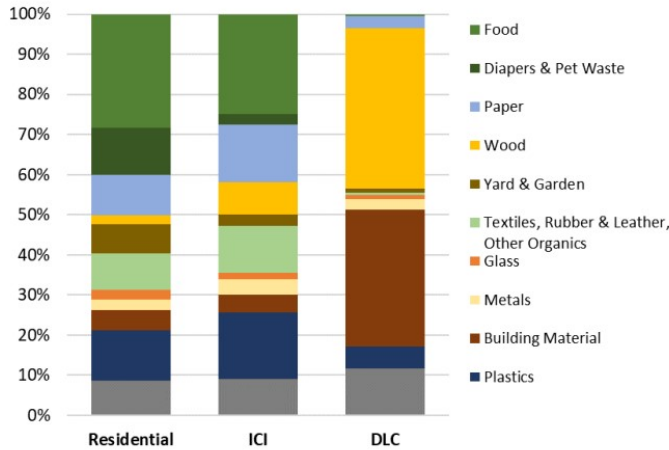


Figure 6. National average % composition of residual MSW, by sector (2016 data)[18]. ICI, industrial, commercial, and institutional; DLC, demolition, land-clearing, and construction. Gray bars are other waste (including electronics, household hazardous, bulky objects).

Recently, Environment and Climate Change Canada (ECCC) commissioned a study through Clean Farms to estimate the quantity of plastic waste generated in the agriculture sector and their relative distribution across the country. The study estimated 61,754 tonnes of agricultural plastics wastes are generated annually at the national level. The prairie provinces generated approximately 23% each of the agricultural plastic waste individually followed by Ontario at approximately 22%[19].

Figure 7 shows the quantity of selected non-degradable waste categories (by weight) disposed in 2016, per sector, as well as the amount diverted for recycling. For this plot, plastics include all plastic material including so-called secondary plastic material categories such as polystyrene, plastic film, PET, HDPE, and plastic resin-based textiles[19].

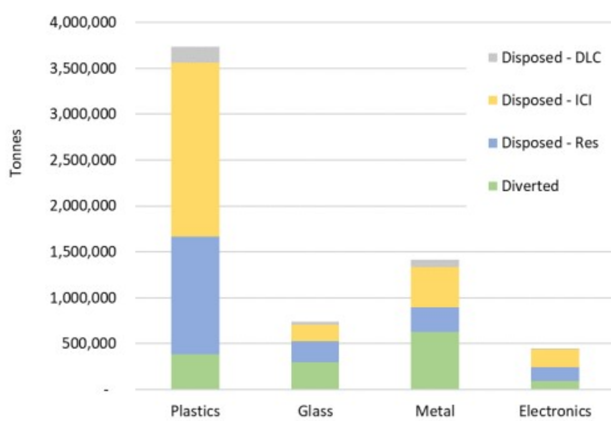


Figure 7. National quantities of selected waste categories disposed and diverted (2016 data)[20]. DLC, demolition, land-clearing, and construction; ICI, industrial, commercial, and institutional; Res, residential.

[19] CLEAN FARMS - Agricultural Plastic Characterization and Management on Canadian Farms, 2021
[20] National Waste Characterization Report (publications.gc.ca)

Figure 7 shows that an average of approximately 3 Mt of plastic is discarded in Canada every year, of which about 9 to 10% is recycled (diverted), leaving the rest to end up in landfill, the environment or to be burned. Currently, 4% of plastic waste is burned, but by 2030 Canada is expected to burn up to 22% of plastic waste[21].

In terms of the situation in Alberta, according to the ECCC study[19], 15% of overall ICI waste generated in Alberta belonged to plastic waste, while about 13% of residential waste were plastic wastes. The quantities (in tonnes) of selected materials in Alberta MSW disposed and diverted in 2016 are shown in Figure 8. The figure shows that approximately 540,000 tonnes of plastic were disposed while only approximately 33,600 tonnes were diverted representing a recycling rate of 5.8%.

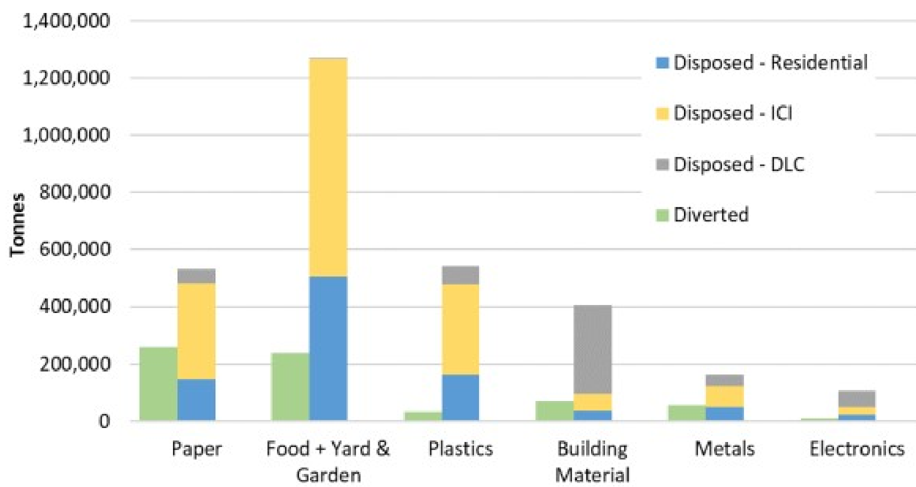
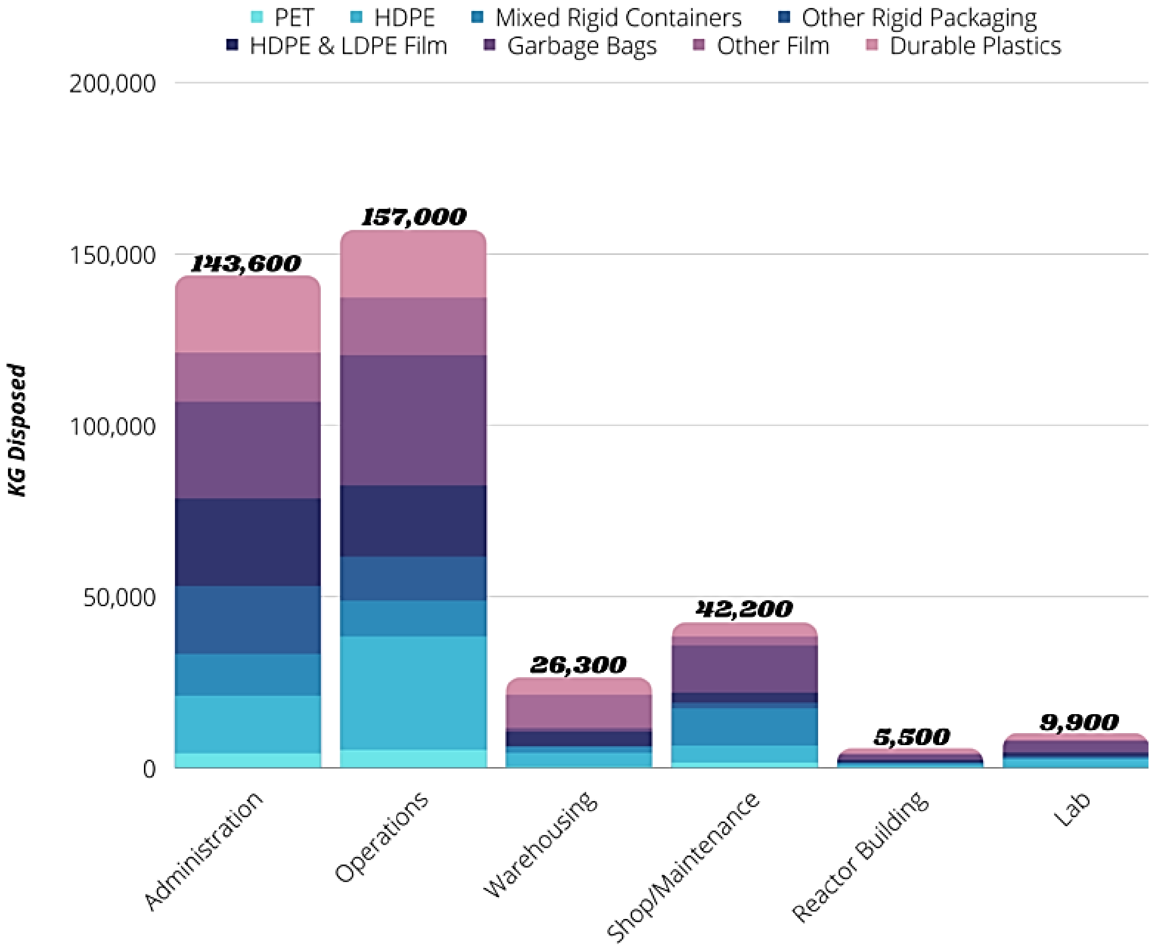


Figure 8. Quantities of select materials in MSW disposed (by sector) and diverted, in tonnes[22].

Alberta Plastic Recycling Association (APRA) undertook a regional study under "the Alberta Plastics Data project" with the goal of collecting and documenting the quantities of plastic resins produced provincially and imported into the province from other nationally international jurisdictions. The Industrial Heartland near Fort Saskatchewan, Alberta was chosen as an area of interest for this study.

The annual tonnage of plastics disposed of from 25 companies across the Alberta's Industrial Heartland Association (AIHA) in 2021 was estimated to be approximately 390 tonnes[23]. In addition to high density polyethylene (HDPE) and low-density polyethylene film, other materials generated included laminated film and shrink wrap and HDPE containers (Figure 9).

[21]https://oceana.ca/en/reports
[22]National Waste Characterization Report (publications.gc.ca)
[23]https://albertaplasticsrecycling.com/programs-projects/alberta-plastics-data-project/



	Administration	Operations	Warehousing	Shop/Maintenance	Reactor Building	Lab
Durable Plastics	22,500	19,900	5,100	4,000	1,400	1,900
Other Film	14,400	16,700	9,700	2,600	400	300
Garbage Bags	28,200	38,000	1,000	13,800	1,500	3,400
HDPE & LDPE Film	25,500	20,900	4,400	2,900	800	1,000
Other Rigid Packaging	19,900	12,800	0	1,600	0	500
Mixed Rigid Containers	12,100	10,400	1,800	10,900	600	400
HDPE	16,900	33,200	4,000	4,900	600	2,300
PET	4,100	5,100	300	1,500	200	100
Total Plastics	**143,600**	**157,000**	**26,300**	**42,200**	**5,500**	**9,900**

Figure 9. Plastics waste data from 25 companies in Alberta's Industrial Heartland[24].

[24] https://albertaplasticsrecycling.com/programs-projects/alberta-plastics-data-project/

On a parallel front, AB Energy and AEPA are assessing plastics feedstock inventory and annual resin usage rates from local as well as imported sources for Alberta. The findings of this plastic resin inventory will better inform various stakeholders about the potential for recycled resins in placing virgin resins with the emphasis on resin stream with larger market potential. The current technical gap assessment compliments all the above initiatives in identifying key technological areas for improving plastic recyclability rates that would benefit from provincial and federal research and innovation support initiatives.

4.2.2 Plastic Waste Management

There are several organizations within Alberta that aim to reduce plastic waste and enhance recycling efforts. These are summarized in the following paragraphs.

In 2020, the Government of Alberta laid out a plan for enhancing plastic recycling in Alberta in their "Getting Alberta Back to Work: Natural Gas Vision and Strategy" document[25]. It outlines a goal of establishing Alberta as Western North America's centre of excellence for plastics diversion and recycling by 2030 focusing on advanced chemical and renewable, low-carbon plastics recycling research and deployment. The plan includes developing province-wide plastics recycling and diversion systems in place and coordinating across jurisdictions to divert plastics for advanced recycling so that critical economies of scale are achieved.

A significant event that is expected to mitigate waste generation and encourage recycling is the introduction of Alberta's new Extended Producer Responsibility (EPR) legislation.[26] The concept of EPR was first introduced in the late 1980s and has since turned into one of the main environmental policy instruments for jurisdictions to reduce waste and inculcate recyclability and circularity into the manufacturing processes. The EPR framework shifts the cost burden of generated end-of life wastes back into producers' fold thus alleviating the municipalities undesired expenses. It incentivizes producers to design environmentally friendly packaging and material with inbuilt longevity and reusability during the course of the material's life cycle.

The Government of Alberta's EPR regulations which came into effect on November 30, 2022, will be regulated through the Alberta Recycling Management Authority (ARMA)[27]. The Alberta Recycling Management Authority (ARMA)[28] was established in 1992, and since its inception has been managing the province's major recycling initiatives. ARMA is a not-for-profit organization incorporated under the Societies Act and operates as a delegated administrative organization accountable to the AEPA. ARMA is authorized to manage four designated materials—electronics, paint, tires, and used oil materials—through a process called multi-material stewardship.

AMRA will develop bylaws and programs through stakeholder engagement to administer the EPR program in the province of Alberta. The whole process of program development and implementation will take up

[25] https://www.alberta.ca/natural-gas-vision-and-strategy.aspx
[26] https://www.alberta.ca/regulated-extended-producer-responsibility-programs.aspx
[27] https://www.albertarecycling.ca/
[28] https://www.albertarecycling.ca/programs/alberta-recycling-resources/

to two years. Thus, Alberta's EPR system is expected to launch in spring 2025. Under the current scheme, Alberta will get two EPR related regulations or bylaws: 1) single-use products, packaging and printed paper (PPP) and 2) hazardous and special products (HSP). These include beverage containers, electronics (computers, accessories, IT equipment, and TVs) and automotive (tires, used oil, oil containers, and filters). A voluntary EPR program is also being developed in which such things as cellphones, pesticides/fertilizers and containers and a plastic bag program are targeted. Going forward, EPR systems are looking at the use of barcodes and tracking to sort plastics and electronics and track their actual recycling costs. The use of this type of technology would enhance the automation of recycling facilities, thus reducing overall operational costs.

The Recycling Council of Alberta (RCA)[29] is another organization focused on advancing plastics circularity in Alberta through waste reduction and resource conservation. They have projects underway including a provincial pilot program to recycle grain bags and twine.

The Plastics Alliance of Alberta (PAA)[30] is a collaboration between industry, government, academia, and non-government organizations representing Alberta's plastics value chain and was formed in July 2020. It has four main objectives that set the strategic direction for their activities:

1. Policy – recommending policies to provincial and municipal governments in Alberta that set the regulatory and investment climate to encourage a circular economy.
2. Investment – defining Alberta's plastics value chain and identifying investment opportunities to achieve a circular economy.
3. Innovation – identifying areas within Alberta's plastics value chain where innovation plays a role in overcoming gaps or barriers to plastics circularity.
4. Awareness – communicating and building awareness of the importance of a circular economy for plastics in Alberta.

The Alberta Plastics Recycling Association (APRA)[31] is another not-for-profit association in the province working in the space of plastic waste diversion, recycling, and reuse. Its membership includes plastics resin producers, manufacturers, fabricators, converters, wholesalers, and retailers of plastic products, along with plastics recyclers and other members of the recycling community. It was instrumental in the establishment of plastics recycling initiatives for used oil containers, milk containers and expanded polystyrene (EPS).

Plastic Research in Action (PRIA)[32] is a limited term research partnership between NAIT (Northern Alberta Institute of Technology) and Heartland Polymers. It is specifically dedicated to finding real-world solutions for various plastic waste streams generated through Heartland Polymers operations and convert those finding for the wide scale reuse and recycling of plastic wastes in Alberta and beyond.

[29] https://recycle.ab.ca/
[30] https://plasticsalliancealberta.ca/
[31] https://albertaplasticsrecycling.com/about/
[32] https://interpipeline.com/sustainability/environment/plastics-research/

The Province of Alberta is currently running an agricultural-centric recycling pilot program called "Alberta Ag-Plastic. Recycle It!" pilot program to address the challenges associated with plastic waste collection, segregation, and recycling at farms[33]. This pilot program encourages farmers to segregate agricultural plastic waste such as grain bags, silage bags, bale wrap, baling twine and netting for recycling and to promote plastic circularity. The Agricultural Plastic Recycling Group (APRG)[34], made up of over 20 organizations representing agricultural producers, retailers, manufacturers, municipalities, non-profits, and others, operates the **"**Alberta Ag-Plastic. Recycle It!" program for the province in partnership with Cleanfarms. Cleanfarms is a non-profit environmental stewardship organization which is working to find a community-based solution for addressing agricultural waste management issues.

4.3 MARKET POTENTIAL FOR RECYCLED PLASTICS

The global recycled plastics market size was valued at USD 47.60 billion in 2022 and is expected to exhibit a compound annual growth rate (CAGR) of 4.9% from 2023 to 2030. Increasing plastic consumption in the production of light weight components which are used in various industries including building and construction, automotive, electrical and electronics and various other industries is expected to propel the growth of recycled plastics demand over the forecast period[35.]

The polyethylene product segment led the market and accounted for more than 26% share of the global revenue in 2022. It is commonly used in laundry detergents packaging, milk cartons, cutting boards, and garbage bins, among various other applications. This high share is attributable to the rising demand for packaging material in consumer goods, food and beverage, industrial and various other industries.

Polypropylene is extensively used in manufacturing automotive components, packaging and labelling, medical devices, and diverse laboratory equipment among various others owing to its excellent chemical and mechanical properties. It is resistant to several chemical solvents, acids, and bases and have excellent mechanically strength. It is also among the most highly formulated plastics across the globe. Additionally, components produced using polypropylene is fatigue resistant, which is beneficial in building and construction industry for producing plastic hinges, piping systems, consumer-grade daily-use products, manufacturing mats, and carpets and rugs among various other applications. The growth of automotive, packaging, building and construction is expected to drive the demand for recycled polypropylene in the forecasted period.

Canada plastic recycling market stood at 3.08 Mt in 2020 and is forecasted to reach 4.38 Mt by 2030, growing at a compound annual growth rate of 3.15% until 2030. Initiatives and regulations to mitigate plastic waste have resulted in the promotion of recycling. The implementation of a modified policy on Green Procurement[36] is expected to increase the demand for recycled goods among businesses and consumers. By 2030, the country is expecting to reduce the landfills of plastic waste by 90%. An investment between USD 4.3 billion and USD 8.6 billion made by the key stakeholders for the addition of

---

[33]https://cleanfarms.ca/alberta-ag-plastic-recycle-it-program/
[34]https://www.aprg.ca/
[35]https://www.grandviewresearch.com/industry-analysis/recycled-plastics-market#:~:text=The%20global%20recycled%20plastics%20market,4.9%25%20from%202023%20to%202030.
[36]https://www.canada.ca/en/treasury-board-secretariat/services/innovation/greening-government/green-procurement.html

167 new sorting and recycling facilities is expected to increase the revenue generated from plastic recycling across the country. Besides, increasing plastic waste due to the rising demand for packaging on account of the growing e-commerce business is also expected to increase the demand for the plastic recycling market in Canada.

Recently, ECCC commissioned a study to better understand the current state of the Canadian plastics industry. Their findings showed that the plastics manufacturing industry is a significant economic driver with sales being reported at $35 billion in 2017 and supporting over 90,000 jobs across more than 1,900 companies. In comparison, Canada's recycling industry has less than a dozen companies employing about 500 people and generating $350 million[37].

Canada currently has an $7.8 billion lost opportunity to capture plastics for recycling. If this does not change, it is estimated this lost opportunity could rise to $11.1 billion by 2030. Major changes to recycling in Canada could see 90% of plastics avoid landfills by 2030 through new investments in recycling and changes to government regulation and consumer willpower. This represents emissions savings of 1.8 Mt of CO_2e.

[37] https://sherwoodparkchamber.com/albertas-circular-economy-another-piece-to-diversifying-our-economy/

5.0 PLASTICS RECYCLING AND CIRCULARITY TECHNOLOGY GAPS AND CHALLENGES

This section reviews the major challenges and gaps in plastics recycling and circularity technology processes. Innovative solutions under development or demonstration that address these challenges are highlighted as well as potential innovative solutions to address these challenges. There are multiple parallel innovations occurring to tackle plastic waste; some are improvements/enhancements of current recycling methods with particular focus on hard-to-recycle plastics, while others address the production of plastics and material design to enhance recyclability. This section is divided into 4 main challenge areas: 1) recycling processes, 2) hard-to-recycle plastics, 3) material design, and 4) upcycling of polymers for circularity.

5.1 TECHNOLOGY CHALLENGES AND GAPS IN RECYCLING

5.1.1 Challenges in recycling mixed plastic feedstocks

In principle, all types of thermoplastics can be mechanically recycled with little or no quality impairment (Vollmer et al., 2020) including PP, HDPE, LDPE, PET, and PS. However, these materials generally need to be recycled separately from each other (Garcia and Robertson, 2017). The reason for this is that most plastics are immiscible with one another, producing phase-separated mixtures with diminished properties. Even small amounts of contamination of one plastic type with another may change the properties and potentially hinder use of the recycled material. Also, temperature-sensitive plastics, composites, and plastics that do not flow at elevated temperatures (as in the case of thermosets) cannot be processed mechanically. Many plastic recycling companies have insufficient standardization, industrialization, and operational capacity in their operations. This is largely due to the nature of the sector, which is characterized by small, entrepreneurial companies, with management teams that often have limited experience in the professional plastics industry. It is challenging for recycling plants to obtain consistently high-quality feedstocks and pre-sorting of waste is required to keep plastics as pure as possible for recycling. This adds extra cost and time to the operations.

Plastic waste is usually sorted through a sequence of sorting steps including sorting by size, either manually or by means of sieves, sorting out foreign materials (e.g., metal and glass), and sorting by plastic materials (Lange, 2021). The common practice is to sort the various plastics by spreading them on a conveyor belt, identifying the plastic to sort using an infrared detector (e.g., near or short-wave infrared, NIR or SWIR) and sorting it with an actuator or air jet. However, there are limitations to infrared (IR) sensing as HDPE/LDPE, PET/PLA, or black products cannot be identified with conventional NIR detectors (Lange, 2021).

Innovative Technology Solutions:

Advanced sorting of plastics waste. New advances in sorting technologies such as AI (artificial intelligence)-assisted systems to speed up plastic waste classification at processing sites and more effective reverse logistics to ensure high-quality waste flow are being developed and commercialized to replace the standard IR detectors[38]. An example of an advanced sorting system uses hyperspectral imaging spectroscopy (HIS) to recognize a full-shape product. A recent study demonstrated the application of unsupervised machine learning on short wave infrared hyperspectral data to build a model for classification of 12 different plastics (Henriksen, et al., 2022). There is still a need for technology optimization as variables such as camera artifacts, sample area, and surface roughness/texture have an impact on the recorded spectra (Lange, 2021).

There are several start-up companies developing various advanced sorting systems. Grayparrot[39] in the UK has developed an optical sensor waste recognition system that integrates with conveyor belts in MRFs (material recovery facilities) to continuously monitor and analyze the waste streams. It provides information on the waste composition in real-time allowing MRFs to improve recycling efficiencies. Another UK-based company, Recycleye[40], has also developed an automated waste sorting system using a combination of machine learning, optical sensors, and robotics. The Dutch company Veridis[41] developed a waste identification and sorting system based on thermal scanning called MADSCAN™. Unique material fingerprints of different plastics are generated using differential scanning calorimetry mapping which measures with high accuracy changes in the heat capacity, melt and glass transitions, phase changes and curing of plastic materials by temperature.

Tracers: Tracers such as fluorescent pigments incorporated into the plastic substrate can aid in the pre-sorting step at recycling facilities. These fluorescent pigments are only visible under UV light at the sorting plant[42]. Another tracing technology uses digital watermarks, i.e., codes that are integrated into the design of the packaging and can be detected by cameras on high-speed sorting lines. In Europe, the Digital Watermarks Initiative HolyGrail 2.0 was recently launched with the goal to assessing whether a digital technology can enable better sorting and higher-quality recycling rates for packaging in the EU[43]. In Alberta, BASF's reciChain™ tracking program is being piloted; Section 5.3 provides greater details on this program.

Mixed plastics recycling. Recent recycling technology developments aim to eliminate the need to sort plastics in the first place by creating processes that recycle mixed plastics together. The Canadian company Plastonix[44] has developed a patented technology that uses a proprietary organic, non-toxic lipid agent to fuse up to 10 unique plastic material types together without the need to sort or clean. The company claims they can treat all kinds of plastic films, containers, woven and nonwoven fabric, and hard plastic from automobile parts. Their system fuses different types of plastics together into an intermediate product which can then be converted to processable chips or powdered material. The fused material can be further repurposed as a filler or parallel material for virgin plastic resins or converted to a composite material, paving material, or construction units such as block paving stones, tile beams, sheets, or boards. The company also designs and consults on the building of smaller processing systems to locate them

[38] https://www.startus-insights.com/innovators-guide/plastic-recycling-trends-innovation/
[39] https://www.greyparrot.ai/
[40] https://recycleye.com/
[41] https://veridis.tech/
[42] https://packagingeurope.com/sorting-plastic-recycling-tracers-digital-watermarks-tomra-procter-gamble
[43] https://www.digitalwatermarks.eu/
[44] https://plastonixinc.com/

locally where plastic is generated and collected thus allowing for a greater control on the types of plastics collected.

Gaps: Continued enhancements in sorting of plastics waste required to increase sorting accuracy and material retention. Validation of processes able to recycle mixed plastic streams is required.

5.1.2 Challenges in recycling contaminated plastic feedstocks.

Sorted plastics may still not be suitable for direct reprocessing. They may require cleaning to remove dirt and other contaminants from packaged food or from the mixed consumer waste for example. In addition, contamination from colorants, additives, adhesives, and fillers used during plastic production as well as contamination from consumer use, results in yield losses during the recycling process. Cleaning and removal of contaminants is generally imperative for mechanical recycling but might be important for chemical recycling as well (e.g., polymer additives may interfere with catalytic activity, Uekert et al., 2023).

Plastic waste is generally cleaned with hot or cold water, with the assistance of caustic agents or detergents. The cleaning is often integrated in the sorting chain, e.g., after shredding and combined with a sink-float sorting step. However, such washing can be costly as it requires dedicated washing equipment but also a drying step and a wastewater treatment (Lange 2021).

Innovative Technology Solutions:

Dissolution/precipitation processes. Dissolution and or precipitation processes can recover polymers from plastic waste that are free of additives such as pigments. A single solvent or a combination of a solvent and an anti-solvent is used to selectively dissolve a specific polymer. An anti-solvent is then added to precipitate out the polymer of recovery. In between dissolution and precipitation steps, non-dissolved materials (e.g., pigments) are separated from the polymer solution. Although solvents are used in the dissolution/precipitation process this is not strictly a chemical recycling process as usually no bonds are cleaved. A drawback to this process is that separation and recovery of solvents with a high boiling point is energy and time-consuming, particularly when operating at a high solvent/polymer ratio. Hence, the energy needed for solvent evaporation should remain much lower than the energy needed to depolymerize the polymer back to its monomer. The incomplete removal of solvents can negatively affect polymer properties. For organic solvents, dissolution can be relatively slow due to the small plastic/solvent contact area. There are various patented physical recycling methods like CreaSolv®[45] (Figure 10, CreaCycle GmbH), Newcycling®[46] or extended physico-chemical recycling methods like CreaSolv®-PolyStyreneLoop[47]. However, degradation of the polymer's thermomechanical properties can still occur during mechanical recycling, resulting in a lower quality polymer than the original.

[45] https://www.creacycle.de/en/the-process.html
[46] https://www.apk.group/en/newcycling/
[47] https://polystyreneloop.eu/technology/

Other emerging trends in dissolution/precipitation processes included microwave heating or ultrasonic irradiation to speed up dissolution rates and separating plastic mixtures using several solvents that dissolve only certain types of polymers.

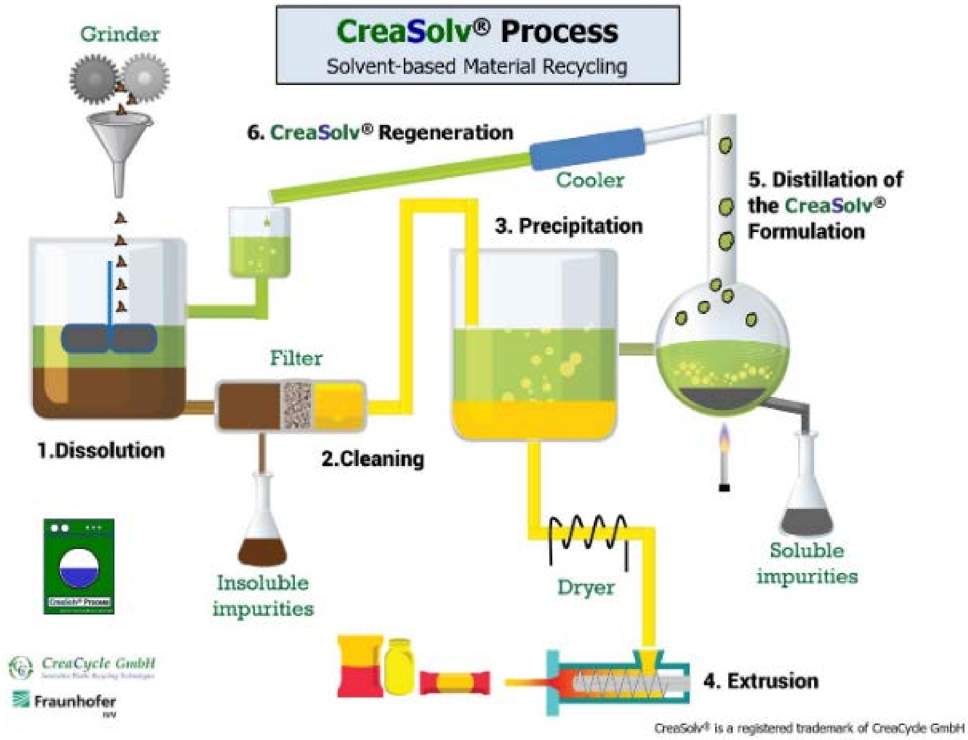


Figure 10. The CreaSolv® process, solvolysis of plastics (https://www.creacycle.de/en/).

Supercritical CO_2. Supercritical CO_2 is being tested as an alternative solvent. Using supercritical CO_2 improves upon the solvent removal and separation step as it will readily evaporate when pressure is decreased. It has the added benefit of avoiding toxic organic solvents such as xylene, acetone, toluene, and n-heptane (Alassali et al., 2020). Supercritical CO_2 is recommended for decontaminating high-quality and high-value plastics resulting in clean feedstocks for recycling. The Spanish plastics technology research organization, AIMPLAS[48], has been investigating the use of supercritical CO_2 to decontaminate post-consumer plastic melt. AIMPLAS has demonstrated the effective removal of volatile organic compounds from recycled printed LDPE film[49].

Novel additives: One critical challenge for the use of mechanically recycled plastic in demanding applications is the often lower and/or fluctuating technical properties of previously used materials. BASF has addressed this issue by developing a new range of additive solutions called IrgaCycle™[50]. Additive solutions designed for the diverse problems encountered when using recyclates can improve the material properties in order to fulfil the requirements of different applications. In many cases, using the

[48] https://www.aimplas.net/
[49] https://resource-recycling.com/plastics/2021/09/15/how-supercritical-co2-can-lead-to-cleaner-recycled-resin/
[50] https://www.basf.com/tw/en/media/news-releases/asia-pacific/2021/09/basf_introduces_irgacycle_mechanical_recycling.html

appropriate additive package can restore the quality and subsequent performance of the recycled material to nearly that of virgin plastic.

Gap: Continue development of innovative pre-treatment or post-treatment technologies that increase material retention and quality while reducing environmental impacts (e.g., toxic solvents, energy efficiencies).

5.1.3 *Challenges in chemical recycling: solvolysis and other depolymerization processes*

Solvolysis is a process in which a chemical reaction of a solvent and solute results in the formation of new components (Vollmer et al., 2020). Several different chemical reactions can occur depending on the process including hydrolysis, alcolysis (glycolysis and methanolysis), phosphorolysis, ammonolysis and aminolysis. These reactions all cleave ether, ester, and acid amid bonds and therefore the processes are limited to polymers with these bonds: PET, PU, PA, PC and PLA. The solvolysis process cannot be used to break C-C bonds. The monomers that are obtained from solvolysis can be further purified by filtering out additives and colorants thus allowing the monomers to be re-polymerized to virgin-grade quality. Monomers can also be mixed with conventionally obtained virgin monomers for polymer synthesis. There are several limitations or disadvantages to the solvolysis process including high energy requirements due to high operating temperatures and the need to separate the liquid cleavage agent and other by-products.

Innovative Technology Solutions:

Supercritical fluids. An emerging trend in solvolysis is using supercritical fluids (e.g., H_2O) to depolymerize polyolefins (Colnik et al., 2022). By tuning the applied temperature and pressure of the supercritical fluids (plus acid/basic properties of water), solvation can be altered making them catalytically active. The advantages of using supercritical water over other chemical recycling methods include better process performances, improved cost efficiencies and lower environmental impacts. It may potentially be useful for processing difficult to handle waste such as mixed plastics and plastics contaminated with organic waste (Colnik et al, 2022). Recently, the UK-based engineering consultant company Stopford licensed the supercritical water recycling process developed at the University of Birmingham[51]. The process, called CircuPlast, uses high-temperature and high-pressure to convert waste plastic into naphtha for primary plastics manufacturing[52].

Eutectic solvents. Eutectic solvents are two solids, which when combined have a low melting point and can act as acid or base through functionality choice. It has been used for PET glycolysis leading to high selectivity to the monomer BHET (Ellis et al., 2021).

Other innovative solvolysis developments. A drawback to solvolysis is that there are complex phase phenomena of certain polymer/solvent combinations which results in temperature, concentration and/or molecular weight dependent de-mixing behavior and a narrow window for solubilization. To overcome this there are non-catalytic reaction engineering strategies under investigation including co-reactant

[51] https://www.recycling-magazine.com/2022/02/10/a-new-supercritical-water-approach-to-recycling-plastic-packaging-waste/
[52] https://www.stopford.co.uk/capabilities-circuplast

addition (e.g., steam), microwave-assisted pyrolysis, supercritical solvents, and solubilization of polymer in oil or solvent before pyrolysis. To address the environmental impacts of using potentially hazardous and toxic solvents (e.g., xylene for polyolefins, benzyl alcohol for PET (Uekert et al., 2023)) and antisolvents (hexane for polyolefins, methanol for PET), biobased solvents such as limonene are being tested (Ferreira et al., 2022).

Microwave heating. Microwave heating is being developed as a modified form of pyrolysis. It uses electric energy instead of heat thus reducing the amount of energy and greenhouse gas emissions. This technique can provide a more even temperature profile inside the reactor, as it heats volumetrically, thus leading to faster depolymerization (Vollmer et al, 2020). Companies such as Pyrowave-Canada[53] and Enval-UK[54] are developing this technology at commercial scale. Indeed, Pyrowave is partnering with the tire company Michelin to build a microwave recycling system for tires[55]. There are still some concerns, however, around the environmental impacts of the technology, including the release of toxic residues from plastic additives[56].

Mechanochemical treatments. Mechanochemistry is the application of mechanical stress to cause the homolytic cleavage of polymers and thus radical formation. This can lead to cross-linking and cross-polymerization and can restore the properties of plastic. Mechanical stress can occur in shear-reactors, ball mills as well as during sonication. Mechanochemical effects can also be used to pre-treat waste plastics, facilitating pyrolysis (e.g., ball milling in the presence of dry CaO_3 assisted the de-chlorination of polyvinyl chloride (PVC)). Exploding ultrasonic bubbles have been tested for breaking up the polymers into oligomers to improve their solubility in different solvents.

Gaps: Development of solvents that can dissolve the polymer at low temperatures to minimize heat requirements and have low-boiling points to enable energy-efficient recovery by distillation as well as sufficient removal during drying. New solvolysis processes should also address the high demand for water use in most chemical recycling processes. Novel or alternate depolymerization processes that minimize the use of solvents should be tested. Life-cycle analyses required to understand environmental impacts of processes.

5.1.4 Challenges in chemical recycling: catalysts for depolymerization of plastics

The catalytic depolymerization of plastic is a complex process and several requirements must be addressed in order to have a successful process (Ellis et al., 2021). An ideal catalytic depolymerization process would be one where the desired reaction pathway has a low reaction barrier, while undesired pathways are prevented from becoming favorable or having appreciable rates. To achieve this, there is first a need for well-characterized and widely available feedstocks. The feedstocks should be characterized using standard analytical methods and include determining the chemical compositions and physical

[53] https://www.pyrowave.com/
[54] https://www.enval.com/
[55] https://www.nationalobserver.com/2021/03/11/microwaves-could-be-future-plastic-recycling
[56] https://www.nationalobserver.com/2021/03/11/microwaves-could-be-future-plastic-recycling

properties of the plastics including molecular weights, melting points and crystallinity. Determining the reaction conditions such as pH, temperature, substrate loadings, and stirring rate is also critical. In this way, rate-limiting reaction barriers and reaction thermodynamics can be understood and optimized.

Innovative Technology Solutions:

Optimization of catalysts. Solid polymers often exhibit high viscosity and low thermal conductivity, such that heat and mass transfer can become a large reaction engineering challenge, highlighting the need for interfacial catalysis. There is often a small contact area between the liquid catalyst and the solid polymer and thus research has been conducted on solid phase reactions. Depolymerization processes wherein polymers are reacted in the solid phase result in kinetics that scale as a function of surface area rather than volumetrically as soluble reactant concentration (Ellis et al., 2021). To overcome these challenges, chemical recycling processes are being designed to enable rapid kinetics on solid substrates or to transform reaction scaling from the surface area to the volumetric concentration of available bonds. As polymer additives may interfere with catalytic activity robust catalysts and processes that are insensitive to additives are being developed.

Biocatalysts as alternates to chemical catalysts. Much effort is being put in by research groups towards the discovery and sourcing of biocatalysts either by environmental screening or by computational (i.e., *in silico*) screening. Even though plastics have only been widely used for 60–70 years, microbial evolution is relatively rapid and bacteria capable of degrading plastic have been discovered (Yoshida et al., 2016).

New prospecting methods using computational approaches have enabled the rapid discovery, optimization, and industrial use of enzymes and engineered microbes for degradation of plastics and plastics-derived intermediates (Ellis et al., 2021). Computational approaches are also useful in either optimizing existing enzymes by random mutagenesis and site-specific mutagenesis on enzyme modeling or by designing new enzymes using machine learning software (Verschoor et al., 2022). Indeed, the BOTTLE™ research consortium built a statistical model to learn the biological rules of known plastic-deconstructing enzymes. The model assigned probabilities to the unique composition of enzymes studied to date and a machine-learning model was built to predict the heat tolerance of enzymes (Gado et al., 2020). The results from this study revealed the model could screen over 250 million proteins in a database to create a short list of promising candidates that had the desired structural features. Further testing confirmed that several of these candidates were able to deconstruct PET, and some were even better at breaking down crystalline PET than amorphous PET. This is a significant finding since crystalline areas within plastics and highly crystalline plastics are known to be recalcitrant to biodegradation.

Another technique to enhance degradation of crystalline regions is to combine chemical with enzymatic treatment. Quartinello et al., 2017 used chemical hydrolysis to treat PET fibers leading to the production of 85% TPA (terephthalic acid). The remaining oligomers were then treated to enzymatic hydrolysis yielding 97% TPA.

Innovations in optimizing biological recycling processes and conditions include modifying biocatalyst' efficacies and enhancing bioreactor operations and engineering thermostable enzymes. An enzyme's thermostability can be very important as the amorphous areas of plastics can become flexible and amenable to enzymatic attack at relatively high temperatures above the plastics' glass transition temperature (Nikolaivits et al., 2021)., research has been conducted in finding solutions to mitigate or overcome this recalcitrance.

Product inhibition relief is critical to the efficient operation of a plastic-degrading bioreactor. One of the most common products of PET hydrolysis is mono(2-hydroxyethyl) terephthalate (MHET) which can act as a competitive inhibitor for PET-hydrolases, hindering the overall degradation of the polymer. One way to combat this competitive inhibition is to use a cocktail of enzymes that are specific to different reactor products (Nikolaivits et al., 2021).

Gaps: Optimization of (bio)catalysts (range of plastics, mixed plastics, reaction rates). Recovery of depolymerized products needs to be optimized.

5.2 Innovations in Recycling Difficult-to-Recycle Plastics and Polymers

5.2.1. Difficult to Recycle Thermoplastics

Although most thermoplastics can be readily recycled, there are some types that have proven to be more difficult to recycle. There are numerous companies and research groups developing technologies to enhance the recyclability of these thermoplastics.

Polyvinyl Chloride. Polyvinyl Chloride, PVC, also known as vinyl, is one of the most widely used plastics worldwide due to its chemical stability and durability. PVC products have an average lifetime of 30 years, with some reaching 50 or more years. PVC waste is difficult to recycle (Table 1) since the presence of additives (stabilizers, colorants, or plasticizers) impedes the recovery of high-quality recycled material (Miliute-Plepiene et al., 2021).

Currently, PVC is being recycled by either mechanical or chemical processes[57]. In mechanical recycling the PVC waste is ground into recyclate granules and melted and remolded into different products. In chemical recycling, pyrolysis, hydrolysis, and heating are used to convert the PVC waste into its chemical components: sodium chloride, calcium chloride, hydrocarbon products and heavy metals. These products are used to produce new PVC, as feed for other manufacturing processes or as fuel for energy recovery. There are still barriers to chemical recycling of PVC as exemplified by the case of the Italian company Solvay. Solvay developed a chemical recycling process called Vinyloop®, using an organic solvent to dissolve PVC composites and separate the PVC polymer from other materials[58]. The process was designed to recycle difficult PVC waste from soft PVC, such as cables and films. However, the company ceased operations since it could not economically separate hazardous low molecular weight phthalate plasticizers from the PVC and consequently it could not meet EU regulations on phthalates[59].

[57] https://www.ecomena.org/recycling-pvc/.
[58] https://www.greenbiz.com/article/vinyloop-hailed-breakthrough-pvc-recycling
[59] https://www.plasteurope.com/news/Closure_of_operation_in_Italy_Phthalates_issue_under_REACH_brings_do_t240095/

Europe is trying to improve the recycling of PVC with such programs as VinylPlus[60]. VinylPlus works in partnership with consumers, businesses, municipalities, waste management companies, recyclers, and converter, as well as the European Commission and national and local governments.

Polystyrene. Polystyrene, PS, is a highly popular plastic packaging material (also known as EPS (expanded polystyrene) Foam or Styrofoam®) which finds wide application in packaging of food items, electronic goods, electrical appliances, and furniture due to its excellent insulating and protective properties. Polystyrene is also used to make useful products such as disposable cups, trays, cutlery, cartons and cases. It is characterized as difficult to recycle mainly due to its inherent bulkiness and occupying large volumes. Because it is bulky, EPS foam takes up storage space and costs more to transport and yet yields only a small amount of polystyrene for re-use or remolding (in fact, polystyrene accounts for only 2% of the volume of uncompacted EPS foams). In addition, PS products that have been used to hold or store food must be thoroughly cleaned to mitigate biocontamination, thus compounding the costs of recycling. At present, it is more economical to produce new EPS foam products than to recycle it, and manufacturers would rather have the higher quality of fresh polystyrene over the recycled one. Thus, there is little economic incentive for recyclers to recycle PS. However, PS can in fact be readily recycled through mechanical and chemical processes.

Styro Re Cycle Ltd.[61] is an Alberta-based company that is recycling EPS, especially white foam and construction foam. It is currently not able to recycle polystyrene used for food products due to biocontamination. It mechanically recycles EPS into manufacturing beads and other products. Polystyvert (Montreal) also recycles PS back into pellets. The company uses a solvent (an essential oil) to dissolve the PS. The company claims the essential oil is very safe and can be easily reused using its patent-pending process to separate the oil from the PS to recycle more material. Recycling Technologies[62] in the UK has developed a patented fluidized bed reactor to convert polystyrene waste back into styrene as shown in Figure 11.

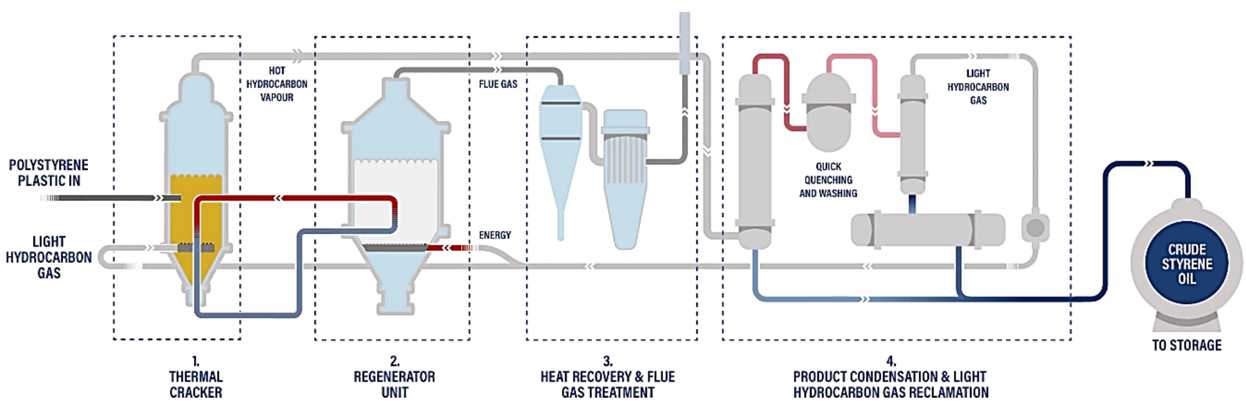


Figure 11. Recycling Technologies' polystyrene chemical recycling technology[63].

[60] https://www.vinylplus.eu/
[61] https://www.styrorecycle.ca/
[62] https://recyclingtechnologies.co.uk/
[63] https://recyclingtechnologies.co.uk/

Polystyrene is also mixed with various chemicals to produce a variety of useful plastic products as shown in Table 8. As the table indicates, most polystyrene products can be recycled easily using mechanical processes, however, most are not accepted at recycling plants due to contaminations issues, and sorting difficulties (i.e., lack of capacity).

Table 8. Characteristics of polystyrene polymers other than EPS**.**

Polystyrene Polymer	Characteristics	Uses	Recyclability
ABS, Acrylonitrile Budtadiene Styrene	• Polymer consisting of three monomers - acrylonitrile, butadiene and styrene, whose shape can be changed as often as desired at certain temperatures, and which is moisture- and dirt-repellent and largely resistant to grease and oil, electrostatic charge and temperature fluctuations. • ABS is stiff, impact- and scratch-resistant and can also be easily bonded, welded and machined	• Main applications for ABS plastics are 40% for household appliances and 26% for electrical and electronic (E&E) applications.[64] • ABS is also used to manufacture toys	• Inherently easy to recycle mechanically. • Contamination from other plastics, and other impurities (e.g., dust, residual metals) impedes recycling. • Colored electronic scrap (i.e., black plastics) make infrared sorting at recycling facilities difficult.
HIPS, High Impact Polystyrene	• HIPS starts as a liquid monomer that is transformed into a stable, solid polymer. • Produced through thermoforming (extruded plastic heated and suctioned into a mold), or by injection molding (forcing melted plastic into a mold cavity). • Known for its strength, crack-resistance and use in low-heat settings.	• Yogurt containers, • Plastic cutlery, • Salad bowls, • Refrigerator lining, • Medical industry trays, • Electrical insulation.	• Inherently easy to recycle mechanically. • HIPS products are given a RIC of 6. • HIPS plastics are often not accepted at recycling plants due to difficulties or lack of capacity to sort the variety of products made from HIPS (e.g., cups, containers, and lids).
SAN, Styrene Acrylonitrile	• Copolymer of styrene and acrylonitrile (the polymer chains are between 70 and 80% by weight styrene and 20 to 30% acrylonitrile. • Larger acrylonitrile content improves mechanical properties and chemical resistance, but also adds a yellow tint to the normally transparent plastic.	• Food containers, • Water bottles, • Kitchenware, • Computer products, • Packaging material, • Battery cases • Plastic optical fibers	• Inherently easy to recycle mechanically. • Contamination and sorting barriers likely preventing widespread recycling of SAN polymers.
SBS, Poly(styrene-butadiene-styrene)	• Copolymer of three segments: polystyrene, polybutadiene, and polystyrene.	• Toys • Sealants and adhesives • Shoe soles • Bitumen products for road paving.	• Inherently easy to recycle mechanically. • Contamination and sorting barriers likely preventing widespread recycling of SAN polymers.

[64] https://www.sesotec.com/emea/en/resources/blog/promoting-plastic-recycling-potential-for-ps-and-abs

Biological recycling of PS has been demonstrated with worms, bacteria, and enzymes (Vershoor et al., 2022). The process of polystyrene depolymerization – converting polystyrene back to its styrene monomer – is also gaining ground (Kumar et al., 2022). Huang et al., 2022 reported on a novel photo-acid-enabled protocol for the selective degradation of polystyrene wastes by molecular oxygen. The process uses mild reaction conditions, and results in the simple chemical recycling of polystyrene waste to valuable chemicals, such as formic acid, benzoic acid, and acetophenone.

Polyamide. Polyamide, PA, is a polymer with repeating units linked by amide bonds. It is commonly known as nylon (invented at DuPont in the 1930s[65]), and includes several varieties, the most common being Nylon 6 and Nylon 6,6. Polyamides are commonly used in textiles, automotive industry, carpets, kitchen utensils and sportswear use to their high durability and strength.

Nylon recycling requires significantly lower temperatures than most plastics, but it is prone to the release of contaminants. Therefore, the material must be thoroughly cleaned before it can be mechanically recycled. This makes the economics of recycling unappealing. However, nylon recycling is increasing in popularity. Aquafil (Italy) recycles old carpets and recovers the Nylon 6 compounds for generating its ECONYL® yarn as well for other reuses in different industrial sectors[66]. Singh and Sharma (2018), reported on the optimization of Polyamide 6 (PA6) recycling using melt processing by screw extrusion. PA6 is an important engineering material which exhibits excellent mechanical properties, chemical resistance, wear resistance, dimensional stability, and low coefficient of friction. The behavior and characteristics of the recycled PA6 polymer were tested to ensure recyclability of PA6 as a property-enhancing extrusion process.

Gaps: Integration of recycling processes for hard-to-recycle thermoplastics into current recycling facilities. Expansion of processes to recycle mixed plastics.

5.2.3. Difficult to Recycle Thermosets

Currently, the bulk of thermoset plastic waste is being managed by landfilling. Other industrial ways to handle thermoset waste are mainly limited to grinding and combustion. Ground thermosets are re-used, typically in the form of fillers, in lower quality applications without separation of the specific constituents and without changing its molecular structure such as aggregates and composites for roads and construction applications. Combustion mainly targets the recovery of the more valuable reinforcing fibers and energy by burning off the thermoset matrix (Pickering 2006). Considering the importance of recovery and valorization of these materials at their end-of-life and the desire to avoid landfilling, interest concerning their recycling grows continuously. For the thermoset materials and their composites to be successfully recovered and valorized, they must be degraded into their three-dimensional structures and the monomers, oligomers and/or fillers recovered.

[65] https://www.sciencehistory.org/distillations/nylon-a-revolution-in-textiles
[66] https://www.aquafil.com/

Thermoset materials can successfully be degraded through thermal treatment at different temperatures (e.g., greater than 1000°C for incineration, and approximately 500°C for oxidation/combustion of organic constituents), chemical degradation by catalysts, irradiation with or without the presence of water, solvolysis., and mechanical recycling, obtaining fine particles that are useful as filler and/or reinforcement additives. Figure 12 shows a schematic diagram summarizing current recycling strategies for thermoset and thermoset-based materials.

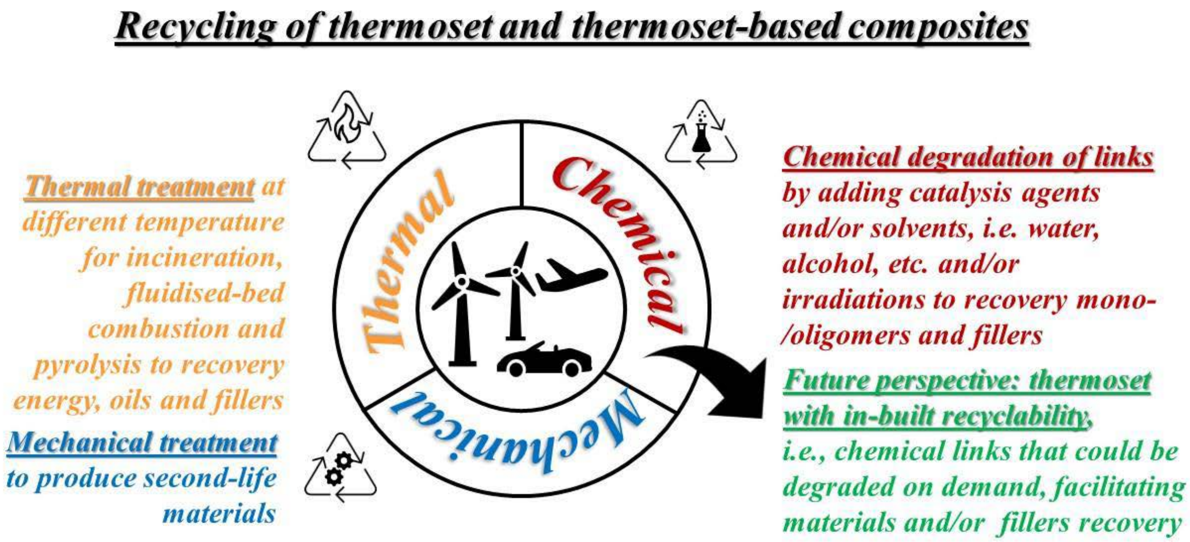


Figure 12. Schematic diagram to summarize current recycling strategies for thermoset and thermoset based composites (Morici et al., 2022).

The recycling of thermoset plastics and materials is becoming ever critical and innovations in recycling processes that are environmentally friendly and financially beneficial for producers and waste management organizations are required. The most important classical thermosets that are recyclable are polyurethanes, epoxies, and silicones, since either valuable material can be recovered, or the output material can be used as building blocks in the manufacturing process of the original plastic material.

Polyurethanes. Polyurethanes are present in very large volumes in the low-density form in insulation foams of mattresses, furniture, and packaging. The production of polyurethane foam in 2020 was 10 Mt and was projected to grow to 17 Mt by 2030[67]. There is inherent value in the materials resulting from polyurethane recycling, and there is a move by industry to recycle or reconstitute almost all polyurethane foam. The end product is typically sold to companies looking for carpet underlayment or pillow filling.

A recent innovation in enhancing the recyclability of thermoset polyurethanes is converting the permanently cross-linked thermosets into vitrimer polymers without depolymerization in a process called vitrimization (Yue et al., 2020, Bandegi et al., 2022). Vitrimers consist of molecular covalent networks which can change their topology by thermally activated bond-exchange reactions. The vitrimized

[67] https://www.marketsandmarkets.com/Market-Reports/polyurethane-market-151784541.html

thermosets exhibited comparable mechanical properties and solvent resistance with the original thermoset polymers but were now recyclable.

Epoxies. Epoxies have inherently no value, but reinforced epoxies are recycled for carbon fiber recovery, which are 10 times more expensive than the epoxy itself. The production of epoxy thermoset composites in 2020 was 2 Mt and was projected to increase to 4 Mt by 2030[30]. Reinforced epoxies are recycled via alcoholysis, where there is typically a catalyzed degradation component of the process. The chemistry is well understood, but there is room for catalysts optimization.

Silicones. Silicones are recycled because of the higher value of silicone monomers, which, for instance, can be used in shampoo formulations as an antifoam agent. Silicones are recycled in a similar way to polyurethanes, but the molecules are broken down to polydimethylsiloxane (PDMS). The recycling process is mostly done on a small scale by silicone users.

Several companies offer recycling technologies that are not targeted to one specific type of thermoset material but to the "difficult to recycle" materials. One example is Recycling Technologies'[68] RT7000 technology that transforms plastic waste into a chemical feedstock for plastic production called Plaxx® (Figure 13).

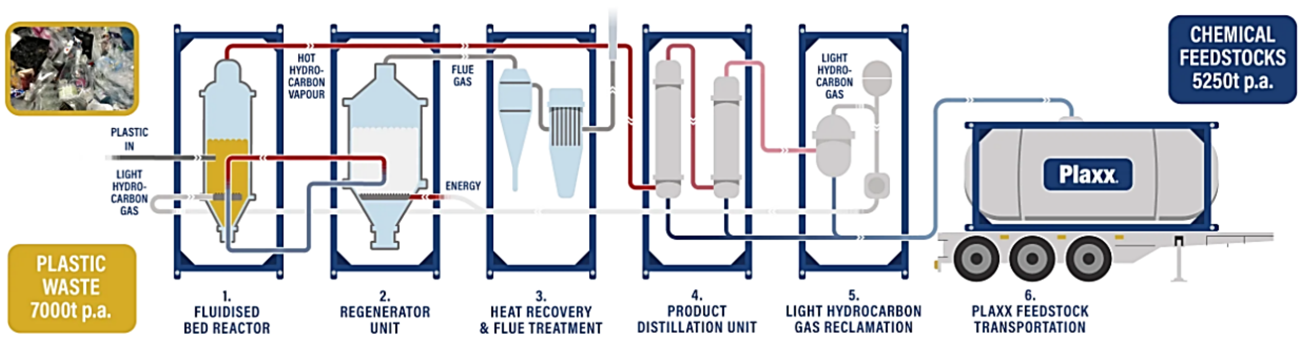


Figure 13. Recycling Technologies' RT7000 plastic waste recycling unit. It transforms plastic waste into chemical feedstock called Plaxx®.

Gaps: Integration of recycling processes for hard-to-recycle thermosets into current recycling facilities. Expansion of processes to recycle mixed plastics.

68 https://recyclingtechnologies.co.uk/

5.3 Technology Gaps in Material Design to Enhance Recyclability

In parallel to technological development around improving recycling processes, activities and research into improving plastics material themselves to enhance recyclability, sustainability and lower environmental impact are occurring. Any new developments in plastic manufacturing would influence downstream, end-of-life recycling processes and thus this section provides an overview of technological activities, challenges and gaps on materials designed for recyclability.

The Canada Plastics Pact[69] organization published a guidance document in 2022 on material design rules for Canadian packaging manufacturing companies that adhere with those of the "Golden Design Rules" put forth by the Consumer Goods Forum[70]. The rules aim to increase progress towards using less and better plastic as well as to achieve the design and plastic use targets laid out in the New Plastics Economy Global Commitment[71]. The Golden Design Rules, a set of voluntary, independent, and time-bound commitments. Amongst the nine Golden Design Rules, rule number 2 is around removing problematic elements from plastic packaging, including limiting the use of additives. Rules 5 (Increase Recycling Value in PET Trays) and 6 (Increase Recycling Value in Flexible Packaging) advocates for the use of mono-material plastics.

Additive-free plastics. Intelligent design with a full cradle-to-cradle life cycle analyses is essential for promoting circularity in the waste plastic sector. Eliminating or reducing use of dyes, coloring agents, binding additives and non-polymeric substances during design phase will facilitate separation and recyclability of different plastic types. By considering these issues at the design stage, it becomes easier to disassemble products into waste fractions that do not contain residues of other material. Through intelligent design the plastic content in end-of-life products can be returned into circulation and used to manufacture new recycled plastic products.

The production of 100 % polyolefin plastics and composites without additives can be achieved with multisite polymerization catalysts and specialized injection-molding processes, such as oscillating packing injection molding (Vollmer et al., 2020). This approach removes the necessity of producing different polymers in different plants, avoids the use of additives, such as glass fiber, and generates a product that could potentially be depolymerized with polymer synthesis catalysts[72].

Mono-material plastics. Flexible packaging commonly includes multi-materials, such as plastic and metalized layers, that cannot be easily separated and are difficult to impossible to recycle. To address this challenge, research and development is being conducted on producing mono-material plastics. Mono-material packaging mainly aims to replace usual multi-material composite layered and/or non-recyclable packaging, in applications ranging from food packaging to the pharmaceutical industry, including personal care products, and even apparel manufacturing.

[69] https://plasticspact.ca/

[70] https://www.theconsumergoodsforum.com/environmental-sustainability/plastic-waste/

[71] https://ellenmacarthurfoundation.org/global-commitment-2022/overview

[72] https://en.wikipedia.org/wiki/Ziegler%E2%80%93Natta_catalyst

There are several criteria that mono-material packaging must meet to be competitive with and eventually replace multi-material packaging including[73]:

- Exhibiting consistent quality, especially for oriented films that protect products from contact with moisture and oxygen.
- Mechanical properties need to be on par with multi-material packaging, specifically elasticity and stiffness, along with the sealability of the thermo-sealed layer.
- Non-interference from coating resins (e.g., printing or labeling).
- Integration into existing recycling processes, for example, there should be mechanisms for effectively identifying mono-material streams and separating smaller fractions by differences in density among the different types of plastics.

The Plastics Engineering Department at University of Massachusetts (Lowell) is developing a new process to produce mono-material plastic film for food packaging that still retains the attractive properties of being low cost, light weight, tough and impervious to oxygen and moisture[74]. Companies that are developing and producing mono-material packaging include Sabic (Saudi Arabia) and Dow (US). Sabic produces a mono biaxially oriented linear low-density polyethylene (LLDPE) film product line suitable for both food and non-food packaging[75]. Dow has combined high- and low-density PE resins to create mono material films for packaging[76]

Novel thermosets. There is a high demand for novel thermosets with polymer architectures that allow for low energy molecular debonding that enables easy matrix removal or recycling. This molecular debonding can be obtained by stimuli-triggered degradation or by introducing dynamic covalent bonds in the networks. These concepts can be subdivided into different mechanisms which are schematically depicted in Figure 14.

[73] https://packagingeurope.com/comment/a-closer-look-at-the-potential-of-the-mono-material-packaging-market/8908.article

[74] https://www.uml.edu/engineering/plastics/

[75] https://www.sabic.com/en/industries/packaging

[76] https://www.dow.com/documents/en-us/mark-prod-info/910/910-00133-01-design-for-recyclability.pdf

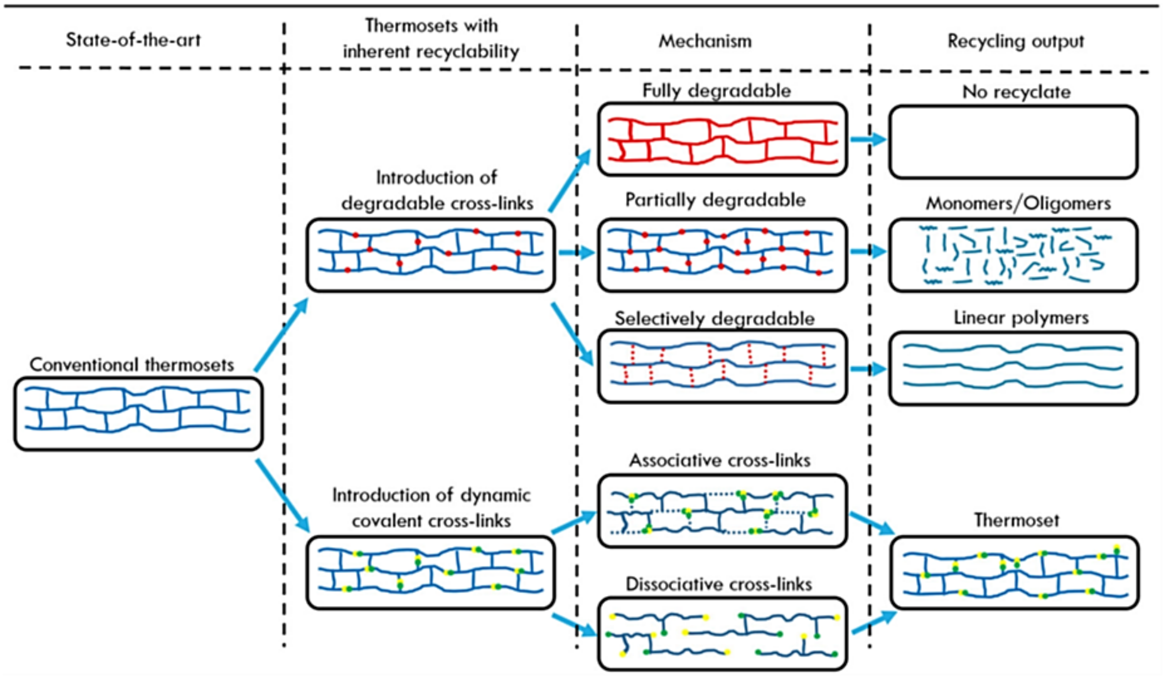


Figure 14. Schematic of current and future recyclable thermosets through intelligent design (Post et al., 2020).

Plastics with tunable degradation capabilities. Research is occurring in the production of polymers with tunable degradation properties, i.e., polymers that degrade under pre-determined conditions into their monomers or oligomers. An example is silyl ether-based cyclic olefins that were copolymerized with norbornene derivatives to produce copolymers with varying stability when exposed to hydrochloric acid (Vollmer et al., 2020). A research consortium in the European Union is developing packaging with built-in biodegradable components. The "TERMINUS" group (in-built **T**riggered **E**nzymes to **R**ecycle **M**ulti-layers an **In**novation for **US**es in plastic packaging)[77] is researching the incorporation of polymers with enzymes. These enzymes have triggered intrinsic self-biodegradation properties. The enzymes in the adhesives or tie layer polymers can facilitate rapid separation of the different layers of packaging at end-of-life as depicted in Figure 15.

[77] https://www.terminus-h2020.eu/

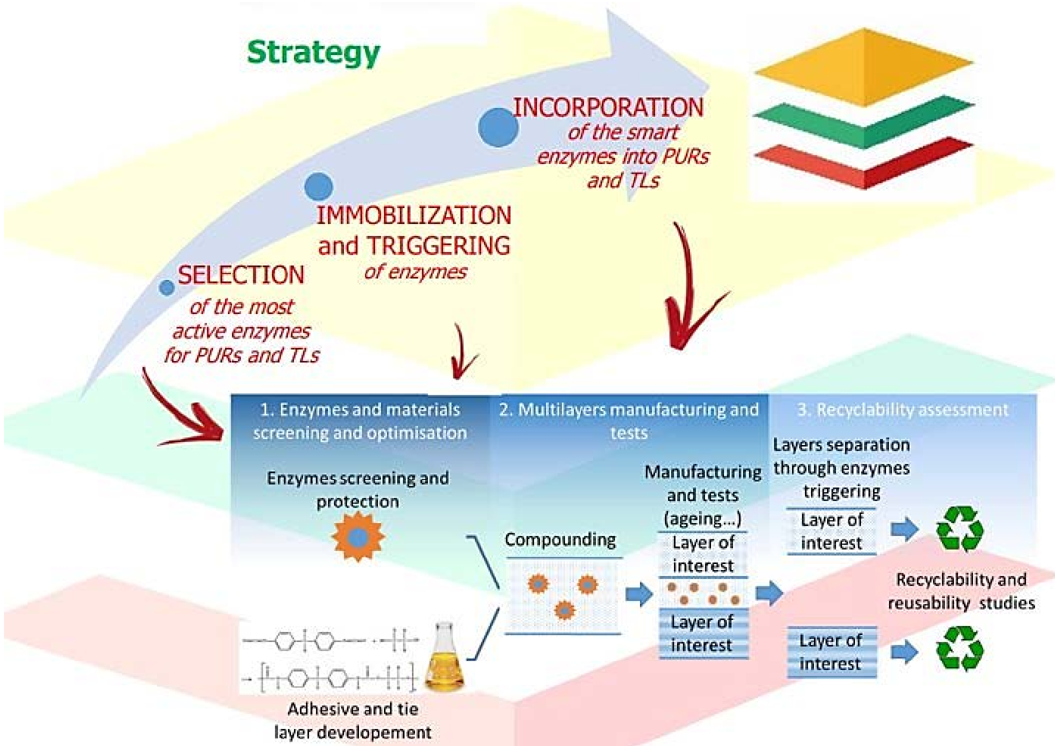


Figure 15. TERMINUS enzymatic degradation technology (https://www.terminus-h2020.eu/).

The technology will be applied to biodegradable PUR-based adhesives for adhesive lamination and extrusion coating lamination, and polymers and tie layers (polybutylene succinate, polylactic acid, polypropylene carbonate, and polycaprolactone) in blown extrusion.

Tracking and Tracing plastics. As mentioned in Section 5.1.1., plastics can be made traceable along their entire value-chain, from production to recycling and re-use, with the incorporation of additives or watermarks in the plastics. The advantages of traceability in plastic recycling are numerous, including guaranteeing the quality of recycled plastic products. By tracking the source and composition of plastic waste, any potential contaminants or impurities that may negatively impact recycling quality or the quality of the recycled end product can be identified and mitigated. Having a fully reliable tracking method for recycled plastic is especially promising for recycled plastic that comes into contact with food since tracking will remove health concerns about the plastic's past use. These technologies hold great promise to not only increase the supply of recycled plastics but to also deter fraud and health concerns in environmental claims citing recycling content percentages (Immell et al., 2020).

BASF Canada recently piloted the reciChain™ program[78] in British Columbia and is now scaling up the technology in Alberta to a semi-commercial level with funding from Alberta Innovates. The reciChain™ technology involves marking plastics with a unique and unalterable chemical-based barcode and connecting them to a digital twin. The barcode is designed to withstand manufacturing and recycling processes. Using proprietary technology in collaboration with Security Matters[79], the barcodes capture a

[78] https://www.basf.com/ca/en/who-we-are/sustainability/Sustainability-in-Canada/reciChain.html
[79] https://recyclinginternational.com/plastics/track-trace-tech-will-help-put-plastic-scrap-on-the-map/30106/

wide variety of information embedded in the plastic which can be used for advanced sorting processes at recycling facilities and to verify sustainability claims. The digital twin is supported by a blockchain marketplace[80] allowing for the auditable transfer-of-ownership and providing incentives to recycle and reuse plastics.

Another example of a traceability system using blockchain technology is TRACKCYCLE. It is being developed and tested by the UK-based recycling company Recycling Technologies[81], along with Circulor[82] and TotalEnergies[83] with support from Innovate UK. The TRACKCYCLE project aims to provide plastic recycling facilities with a fully traceable, precisely labelled record of recycled materials so they can see the provenance and quality of the materials entering and exiting their facilities[84].

Gaps: Continued optimization of designed-for-recycling plastics and verification that their physical-mechanical properties are not compromised.

5.4 Technology Innovations in Upcycling

Instead of depolymerization of plastics to monomers to be then repolymerized into new plastic, plastics can be broken down into specific oligomers and upcycled into more valuable materials. Examples of companies upcycling include GreenMantra[85] which produces polymer additives to tune the properties of inks and coatings for the printing industry making them glossier, easier to print out and more durable.

Other reported examples of upcycling of polymers into more valuable materials include the synthesis of fiber-reinforced plastics, via combination of depolymerized PET with renewably sourced, bio-derived olefinic acids (Rorrer et al., 2019) and the treatment of Nylon-12 and Nylon-6 with supercritical methanol to produce methyl ω-hydroxydodecanoate, a fatty acid ester derivative with potential antimicrobial agent applications with 85% yield (Kamimura et al., 2008).

With regards to polyolefins, Bäckström et al. (2019) reported the selective conversion of HDPE wastes to a few well-defined products, namely, succinic, glutaric, and adipic acid through microwave assisted acidic hydrolysis. The acids were then converted into plasticizers to be used in PLA processing. Succinic acid is highlighted by the US Department of Energy as a key platform for the bio-economy market, while adipic acid is currently the most common dicarboxylic acid produced from petroleum refining with the global market size estimated to be higher than 2.7 Mt per year at a price of above 1500 Euro/tonnes (Vollmer et al., 2020.)

---

80 Real Items
81 https://recyclingtechnologies.co.uk/
82 https://www.circulor.com/
83 TotalEnergies Global Homepage - Renewables and Electricity, Natural Gas and Green Gases, Oil and Biofuels | TotalEnergies.com
84 https://www.packaging-gateway.com/news/recycling-technologies-trackcycle/
85 https://greenmantra.com/

Novoloop[86] uses a proprietary process called ATOD™ (Accelerated Thermal Oxidative Decomposition) to take apart plastic waste, purify, and convert it into high-quality building blocks. It specializes in generating TPU, a thermoplastic polyurethane, Novoloop calls Oistre™. Oistre™ is a melt-processable thermoplastic elastomer with high durability, flexibility, and outstanding abrasion resistance.

Microbial catalysis can funnel plastics-derived intermediates into central metabolism to produce value-added chemicals in a process called bio-upcycling. Table 9 summarizes examples of bio-upcycling reported in the literature.

Table 9. Examples of bio-upcycling products reported in the literature.

Plastic	Monomer Generated	Bio-Upcycled Product	Uses	Reference
PET	BHET	Quaternary ammonium compounds	Softeners for cotton fabrics	Shukla et al., 2008
	TPA	Gallic acid	Antibacterial agent, trimethoprim, and antioxidant- propyl gallate	Nikolaivits at al., 2021
		Pyrogallol	antioxidant in the oil industry	
		Catechol, muconic acid	Used to produce adipic acid, (used to produce plastics)	
		Vanillic acid	direct precursor of vanillin	
PS	Styrene	3-vinylcatechol	Synthesis of polymers, dyes, and pharmaceutical products	Nikolaivits at al., 2021
		Styrene oxide	Reactive plasticizer or diluent for epoxy resins	Mooney et al., 2006
PU		Adipic acid (AA), 1,4- butanediol (BDO), ethylene glycol (EG) and 2,4 TDA	Rhamnolipids	Nikolaivits at al., 2021

Research is occurring in the upcycling of mixed plastic waste through tandem chemical oxidation and bioconversion (Sullivan et al., 2022). In the process depicted in Figure 15, multiple types of polymers are deconstructed using metal-promoted autooxidation, generating a mixture of oxygenated intermediates that are advantaged substrates for bioconversion. An engineered *P. putida* strain funnels the heterogeneous mixture of oxygenates into a single target product.

[86] https://www.novoloop.com/

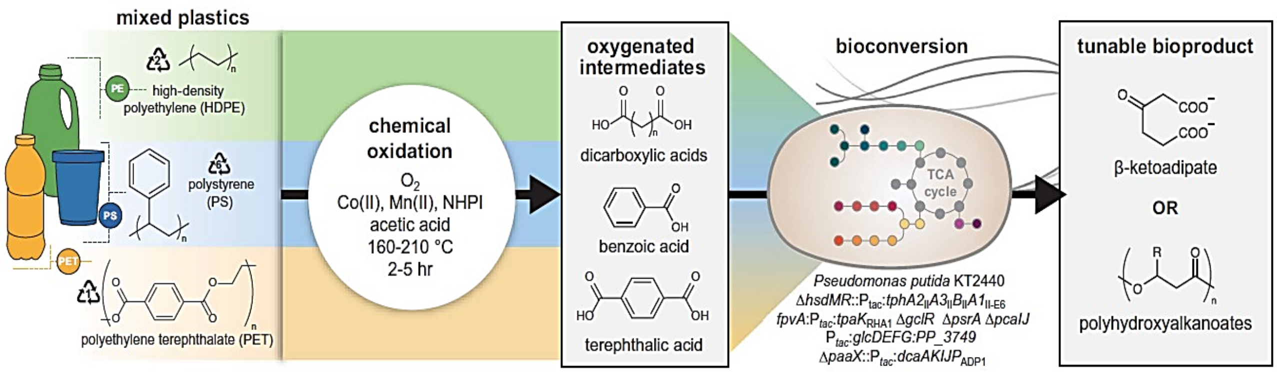


Figure 16. Tandon chemical/biological upcycling process of mixed plastic waste (Sullivan et al., 2022).

Gaps: Requirements for continued process optimizations to ensure upcycling technologies are cost-effective with minimal environmental impacts.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Plastics are a broad family of materials that come in various molecular forms and are used in diverse applications. Therefore, a "one-size fits all' approach will not work to address the plastic waste crisis. Based on the comprehensive assessment of the current state of plastic waste recycling, it is apparent that this sector is still heavily reliant on mechanical and advanced mechanical recycling technologies for generating post-consumer recycled plastics. There is an urgent need to provide innovative solutions and processes to expand the recyclability and reusability of end-of-life plastics beyond Canada's historic 9-10% diversion rates. This technology gap assessment therefore recommends a multi-prong approach to enhance recycling rates and circularity of plastics as summarized below.

Innovative Recycling Processes

Although well established and widely deployed, mechanical recycling suffers from intrinsic deficiencies such as the requirement of single types of plastics and from poor material retention, which can be overcome through source sorting, pre-sorting, and washing. Innovations to address the source segregation and sorting gaps include the design, development and deployment of optical sensors and robotic sorters. Developing digital watermarks or barcodes (such as reciChain™) to track and trace plastics throughout their lifecycle program will greatly aid in the management of plastic volumes and categorizations at recycling facilities.

Selective solvent dissolution removes impurities from plastic waste resulting in the recovery of very high-quality plastics. Supercritical CO_2 is also being tested as an effective and efficient extraction method to decontaminate plastic waste. Concerns around environmental impacts of using potentially toxic and hazardous solvents need to be addressed as well as ensuring material retention and quality are maintained during the dissolution and precipitation steps. Use of benign and/or biogenic and thermally stable (high boiling) solvents, ionic liquids, or low process temperature technologies can alleviate the environmental toxicity issues associated with solvent-based recycling approaches.

Novel recycling technologies that can recycle mixed and contaminated plastic waste can alleviate the need for pre-sorting and cleaning. However, continued quality and functional testing of the recycled products from mixed waste need to be supported to ensure the recyclates are marketable.

Innovative approaches within the chemical and biological recycling domain are still in their infancy and would benefit through applied research and pilot funding to accelerate their time to commercial deployment. Continued improvements in the energy and water requirements and use of non-toxic solvents for most chemical processes would ensure greater adoption by recycling facilities.

Enhancing the recyclability of difficult-to-recycle plastics.

Some plastics are considered difficult to recycle because crosslinking, the presence of additives such as stabilizers, colourants, or plasticizers impede the recovery of high-quality recyclate as in the case of polyvinyl chloride or because of impediments to collection due to their bulkiness as in the case of polystyrene. Innovations in mechanical and chemical recycling can greatly increase the types of plastics that can be recycled including those that are traditionally considered difficult to recycle. Any new technology that is developed to enhance the range of plastics recycled should be evaluated for integration into current recycling facilities as well as address its environmental impacts. Innovative hybrid recycling approaches, where two or more recycling processes are integrated in a synergistic fashion, could expand the types of plastics that are recycled into quality recyclates.

Innovations in plastic material design to enhance recyclability.

Many products are manufactured in ways that make the plastic content difficult to separate and, therefore, recycle. For example, different plastic types may be combined or other materials, such as glue, ink, paper, and metals, bonded or fixed to the plastic. By considering these issues at the design stage, it becomes easier to disassemble products into waste fractions that do not contain residues of other material. New polymer chemistries that are recyclable by design would provide a promising opportunity for recyclers to upcycle plastic wastes and incentivize closed-loop collection. Design for recycling is supported by the Canada Plastics Pact which have put forth “Golden Design Rules” for manufacturers to produce more environmentally friendly packaging and products. New materials may require certain functional properties and product performance matching or exceeding conventional plastics, which would constitute a major domain for applied research and development.

Innovations in plastic upcycling technologies.

Breaking down plastic waste into its oligomers and monomers allows recyclers to recover a greater fraction of materials from the waste source and promote in the establishment of plastic circular economy. To recover oligomer/monomer components from waste streams, startups leverage both chemical and biological means. For example, enzymatic recycling uses bacterial catalysts to break down plastic waste into high-quality monomers. This allows plastic recyclers to ensure the quality of the recyclates and generate high commercial value as monomers directly replace fossil-fuel-based raw materials in plastic manufacturing industries. These kinds of technologies are typically at a lower technology readiness level, and improvements in oligomer/monomer recovery, operational efficiencies, and scalability as well as abilities to treat mixed and contaminated plastic waste are needed. Upcycling options improve plastic waste recycling economics.

Alberta, with its rich resources in plastic production and innovation, can help to accelerate and realize a working plastic circular economy in the province as well as in Canada. Collaborative research amongst stakeholders across the plastic production, recycling and innovation domain would ensure realization of a centre of excellence in plastic circularity in Alberta.

7.0 REFERENCES

Alassali, A., Aboud, N., Kuchta. K., Jaeger, P., Zeinolebadi, A. (2020) Assessment of supercritical CO_2 extraction as a method for plastic waste decontamination. Polymers 12:1347.

Andrady A.L., Neal M.A. (2009) Applications and societal benefits of plastics. Philos Trans R Soc B 364:1977–1984.

Bäckström E., Odelius K., Hakkarainen M. (2019) Designed from Recycled: Turning Polyethylene Waste to Covalently Attached Polylactide Plasticizers. ACS Sustainable Chem. Eng. 7:11004–11013.

Balu, R., Dutta, N.K., Roy Choudhury, N. (2022) Plastic waste upcycling: a sustainable solution for waste management, product development, and circular economy. Polymers 2022, 14, 4788. https://doi.org/10.3390/polym14224788.

Bandegi, A., Montemayor, M., Manas-Zloczower, I. (2022) Vitrimerization of rigid thermoset polyurethane foams: A mechanochemical method to recycle and reprocess thermosets. Polym Adv Technol. 33:3750–3758.

Beckman, E. (2018) The world of plastics, in numbers. The Conversation, http://theconversation.com/the-world-of-plastics-in-numbers-100291. Accessed February 11, 2019.

Colnik, M., Kotnik, P., Knez, Z., Skerget, M. (2022) Chemical recycling of polyolefins waste materials using supercritical water. Polymers 14:4415.

Cregut, M., Bedas, M., Durand, M.J., and Thouand, G. (2013) New insights into polyurethane biodegradation and realistic prospects for the development of a sustainable waste recycling process. Biotechnol Adv 31: 1634–1647. doi: 10.3389/fbioe.2021.696040.

Ellis, L.D., Rorrer, N.A., Sullivan, K.P., Otto, M., McGeehan, J.E., Roman-Leshkov, Y., Wierckx, N. Beckham, G.T. (2021) Chemical and biological catalysis for plastics recycling and upcycling. Nature Catalysis 4(July 2021):539-536.

Gado, J.E., Beckham, G.T., Payne, C.M. (2020) Improving enzyme optimum temperature prediction with resampling strategies and ensemble learning. *J. Chem Inf Model*. *60*(8):4098-4107.

Garcia, J.M., Robertson, M.L. (2017) The future of plastics recycling. Science 358 (6365):870-872.

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

Green, K.P. (2021). Canada's Wasteful Plan to Regulate Plastic Waste. Fraser Institute.

Ferreira, A.M., Sucena, I., Otero, V., Mariasole Angelin, E., João Melo, M., Coutinho, J.A.P. (2022) Pretreatment of Plastic Waste: Removal of Colorants from HDPE Using Biosolvents. *Molecules 27*(1), 98; https://doi.org/10.3390/molecules27010098

Henriksen, M.L., Karlsen, C.B., Klarskov, P., Hinge, M. (2022) Plastic classification via in-line hyperspectral camera analysis and unsupervised machine learning. Vibrational Spectroscopy 118:103329.

Hopewell, J., Dvorak, R., Koslor, E. (2009) Plastics Recycling: Challenges and opportunities philosophical transactions of the royal society b biological sciences 364(1526):2115-26.

Huang, Z., Shanmugam, M., Liu, Z., Brookfield, A., Bennet, E.L., Guan, R., Vega Herrera, D.E., Lopez-Sanchez, J.A., Slater, A.G., McInnes, E.J.L., Qi**,** X.**,** Jianliang Xiao, (2022) Chemical recycling of polystyrene to valuable chemicals via selective acid-catalyzed aerobic oxidation under visible light *J. Am. Chem. Soc.*, 144, 14, 6532–6542.

Immell, T., Yang, W., Quan, L., Farling, S., Patel, P., Shanmuganathan, S. (2020) A Roadmap to support the circularity and recycling of plastics in Canada – Technical standards, regulations and research, September 2020.

Kamimura A., Oishi Y., Kaiso K., Sugimoto T., Kashiwagi K. (2008) Supercritical secondary alcohols as useful media to convert polyamide into monomeric lactams. ChemSusChem 1:82–84.

Kumar, V., Khan, A., Rabnawaz, M. (2022) Efficient depolymerization of polystyrene with table salt and oxidized copper. ACS Sustainable Chem. Eng. 10(19): 6493-6502.

Lange, J-P. (2021) Managing Plastic Waste–Sorting, Recycling, Disposal, and Product Redesign.*ACS Sustainable Chemistry & Engineering 9*(47), 15722-15738DOI: 10.1021/acssuschemeng.1c05013.

Miliute-Plepiene, J., Frane, A., Amasi, A.M. (2021) Overview of polyvinyl chloride (PVC) waste management practices in Nordic countries. Cleaner Eng. Technol. 4:100246 https://doi.org/10.1016/j.clet.2021.100246.

Mooney, A., Ward, P.G., O'Connor, K.E. (2006) Microbial degradation of styrene: biochemistry, molecular genetics, and perspectives for biotechnological applications. Appl. Microbiol. Biotechnol. 72:1.

Morici, E., Dithecal, N.Tz (2022) Recycling of thermoset materials and thermoset-based composites: challenge and opportunity, Polymers 2022, 14, 4153. https://doi.org/10.3390/polym14194153.

Nikolaivits, E., Pantelic, B., Azeem, M., Taxeidis, G., Babu, R., Topakas, E., Brennan Fournet, M. and Nikodinovic-Runic, J. (2021) Progressing plastics circularity: A review of mechano-biocatalytic approaches for waste plastic (re)valorization. Front. Bioeng. Biotechnol. 9:696040.

Parker, L. (2018) Pervasive plastics. National Geographic Magazine, June 2018. pp.40-19.

Pickering, S.J. (2006) Recycling technologies for thermoset composite materials – current status. Compos. Part A: Appl. Sci. Manufact. 2006, 37, 1206–1215. DOI: 10.1016/j.compositesa.2005.05.030.

Post, W., Susa, A., Blaauw, R., Molenveld, K., Knoop, R.J.I. (2020) A Review on the Potential and Limitations of Recyclable Thermosets for Structural Applications, Polymer Reviews, 2020, vol. 60, no. 2, 359–388, https://doi.org/10.1080/15583724.2019.1673406.

Quartinello, F., Vajnhandl, S., Volmajer Valh, J., Farmer, T.J., Voncina, B., Lobnik, A. et al. (2017) Synergistic chemo-enzymatic hydrolysis of poly(ethylene terephthalate) from textile waste. Microb. Biotechnol. 10:1376-1383.

Restrepo-Florez, J.M., Bassi, A., Thompson, M.R. (2014) Microbial degradation and deterioration of polyethylene—-a review. Int Biodeterior Biodegrad 88:83–90.

Rorrer, N.A., Nicholson, S., Carpenter, A., Biddy, M.J., Grundl, N.J., Beckham, G.T. (2019) Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling. Joule 3:1006–1027.

Shamsuyeva, M., Endres, H.-J. (2021) Plastics in the context of the circular economy and sustainable plastics recycling: comprehensive review on research development, standardization and market, Composites Part C: Open Access 6 100168.

Shukla, S., Harad, A.M., Jawale, L.S. (2008) Recycling of waste PET into useful textile auxiliaries. Waste. Manage. 28:51-56.

Singh B, Sharma N (2008) Mechanistic implications of plastic degradation. Polym Degrad Stab 93:561–584

Sullivan, K.P., Werner, A.Z., Ramirez, K.J., Lucas D., Ellis, L.D., Bussard, J.R., Black, B.A., Brandner, D.G., Bratti, F., Buss, B.L. Dong, X., Haugen, S.J., Ingraham, M.A., Konev, M.O., Michener, W.E., Miscall, J., Pardo, I., Woodworth, S.P., Guss, A.M., Román-Leshkov, Y., Stahl, S.S., Beckham, G.T. (2022) Mixed plastics waste valorization through tandem chemical oxidation and biological funneling. Science 378, 207–211

The Economist Group. 2021. Rethinking plastics in a circular economy. Economist impact and world ocean initiative. https://ocean.economist.com/rethinking-plastics/assessment/.

Tokiwa, Y., Calabia, B., Ugwu, C., and Aiba, S. (2009) Biodegradability of plastics. Int J Mol Sci 10: 3722.

Uekert, T., Singh, A., DesVeaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., Afzal, S., Walzberg, J., Knauer, K.M., Nicholson, S.R., Beckham, G.T., Carpenter, A.C. (2023) Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. CS Sustainable Chem. Eng. 11(3):965–978

Verschoor, J.-A., Kusumawardhani, H., Ram, A.F.J., de Winde, J.H. (2022) Toward microbial recycling and upcycling of plastics: prospects and challenges. Front. Microbiol. 13:821629.

Vollmer, I., Jenks, M.J.F., Roelands, M.C.P., White, R.J., van Harmelen, T., de Wild, P., van der Laan, G.P., Meirer, F., Keurentjes, J.T.F., Weckhuysen, B.M. (2020) Beyond mechanical recycling: giving new life to plastic waste. Angew. Chem. Int. Ed. 59:15402-15423.

Webb, H., Arnott, J., Crawford, R., and Ivanova, E. (2013) Plastic degradation and its environmental implications with special reference to poly(ethylene terephthalate). Polymers 5: 1.

Wei, R., Zimmermann, W. (2017) Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? Microbial Biotechnology 10(6): 1308-1322.

Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y. Oda, K. (2016) A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 351:1196-1199.

Yue, L., Guo, H., Kennedy, A., Patel, A., Gong, X., Ju, T., Gray, T., Manas-Zloczower, I. (2020) Vitrimerization: Converting Thermoset Polymers into Vitrimers. ACS Macro Lett. 2020, 9, 6, 836–842 https://doi.org/10.1021/acsmacrolett.0c00299

Zheng, Y., Yanful, E.K., and Bassi, A.S. (2005) A review of plastic waste biodegradation. Crit Rev Biotechnol 25:243–250.