STANDARDS RESEARCH

Defining Recycling in the Context of Plastics

A Principled and Practical Approach

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Authors

Usman Valiante, Cardwell Grove Inc.

Glenda Gies, Glenda Gies and Associates Inc.

Emma Moreside, University of British Columbia

Advisory Panel

Alexander Devonish, Environment and Climate Change Canada

Andy Dabydeen, Canadian Tire Corporation

Cosmin Vasile, Quebec Ministry of Environment and Fight against Climate Change

Isabelle Couture, Plastic-Free YYC

Joanne Fedyk, Saskatchewan Waste Reduction Council

Shannon Lavalley, Circular Innovation Council

Ana-Maria Tomlinson, CSA Group

Hélène Vaillancourt, CSA Group

Michael Leering, CSA Group

Shamily Shanmuganathan, CSA Group (Project Lead)

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Executive Summary

There is no consistent definition of recycling in Canada. Many of the definitions in current usage include a long list of possible activities (e.g., collecting, transporting, handling, storing, disassembling, dismantling, sorting, separating, shredding, processing, remanufacturing) that create confusion about which step constitutes "recycling" and whether "recycling" has occurred at the completion of any step.

A clear definition of recycling is important to both public policymakers that are seeking to achieve specific environmental outcomes associated with recycling of materials and to the regulated community that must deliver them. It is also of importance to the plastics recycling sector as it will determine plastics collection, sorting, and recycling supply chain design and attendant infrastructure investments towards driving a circular economy for plastics in Canada. As such, the purpose of this research study is to propose a definition of recycling that can be used to develop a plastics recycling standard.

The research for this report was conducted by undertaking a scan of the scientific and technical literature to summarize the physical and chemical processes to make and recycle plastics, a review of existing definitions of recycling, and a jurisdictional scan of various definitions of recycling adopted by the European Union, ten American states, and all Canadian provinces and territories. In addition, a – questionnaire based survey was conducted of the production, use, and recycling value chain of plastic packaging to understand its views on the definition of recycling.

Fossil-based plastics – polyethylene, polypropylene, polystyrene, etc. – are highly ordered molecules not found in nature. They are created by using energy (primarily from fossil resources) to reform base hydrocarbons found in oil and natural gas as well as other elements into monomers (single-unit molecular building blocks) and polymers (chain-like structures made of single-unit molecular plastic building blocks).

Plastics may also be produced from biological sources (typically plant-based biomass). These can be manufactured as either biodegradable plastics [1] (broken down by the action of bacteria or other living organisms) or as chemically identical "drop-in" substitutes for fossil-based plastics such as polyethylene terephthalate (PET). These chemically identical biomass-derived fossil plastic substitutes can be recycled in conventional recycling systems that typically recycle fossil-based plastics.

Under circular economy (CE) principles, recycling takes different forms for fossil-based and non-fossil plastics. For fossil-based plastics, the objective is to use renewable energy to reclaim fossil resources and avoid the waste (e.g., GHG, other air pollutants, effluents) associated with its production from fossil resources, while minimizing how much of the same wastes are generated in undertaking that reclamation. For non-fossil (bio-based) plastics, the objective is to return nutrients in those plastics to biological systems to support regeneration or to reclaim the hydrocarbons in those plastics to displace the use of primary or raw materials.

All plastics (fossil or bio-based) and all plastics recycling methods and technologies either in use or just emerging can be evaluated within the CE framework of recycling.

Consistent with CE principles, the following working definition of recycling is proposed:

> *Recycling is the reclamation of materials in such a manner that they can be used to displace the primary or raw materials they were produced from.*

In the context of plastics, this definition can be stated as:

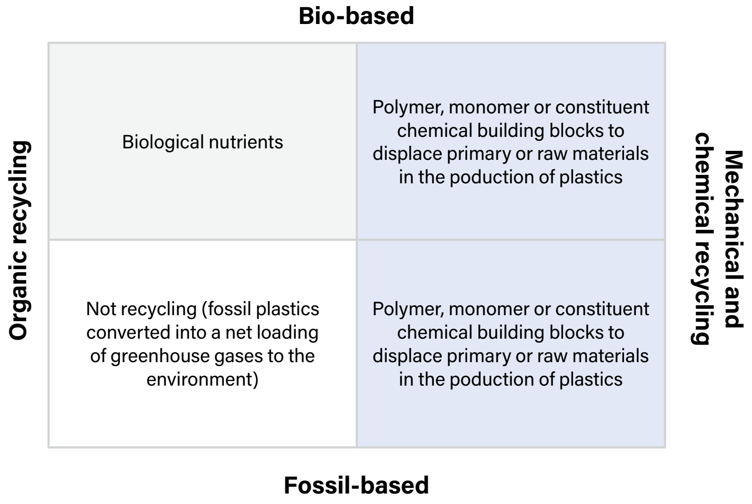
> *Recycling is the reclamation of plastics (as polymer, monomer, or constituent chemical building blocks) in such a manner that they displace the primary or raw materials that are used as chemical building blocks in the production of plastics and plastic products and packaging.*

In the context of bio-based plastics, this definition can be stated as:

> *Organic recycling is the processing of bio-based plastics into biological nutrients.*

Under circular economy principles, only organic recycling of bio-based plastics is recognized as recycling. The definition of recycling in the context of its production pathways is summarized in Figure E1.

Figure E1: Production and recycling of plastics



	Organic recycling	Mechanical and chemical recycling
Bio-based	Biological nutrients	Polymer, monomer or constituent chemical building blocks to displace primary or raw materials in the poduction of plastics
Fossil-based	Not recycling (fossil plastics converted into a net loading of greenhouse gases to the environment)	Polymer, monomer or constituent chemical building blocks to displace primary or raw materials in the poduction of plastics

A recycling standard built upon the proposed definition will require the following elements to be developed as part of the standard:

- Specifications for reporting the amount of plastic supplied into the market;
- A specification establishing a measurement point where plastics are deemed recycled consistent with the definition of recycling;
- A specification for calculating the recycling rate as the amount of recycled plastic produced at the measuring point expressed as a percentage of the total amount of plastic supplied into the market;
- Specifications or performing mass balance calculations in chemical recycling pathways where recycled chemical carriers are produced and blended into virgin production supply chains. Such rules are not only critical for verifying the recycling of plastics but also for establishing claims of plastics recycled content made by producers of resins and plastic products; and
- Specifications and standards for verifying the processing of non-fossil, bio-based plastics into biological nutrients.

Development of such rules will require broad industry consultation with producers of products using plastics or plastic packaging, mechanical and chemical recyclers of plastics, and plastic resin producers.

"In October 2020, the Government of Canada announced proposed next steps to achieve the goal of zero plastic waste by 2030."

1 Introduction

1.1 Canada's Emerging Policy Landscape on Plastic Waste

Across Canada, federal, provincial, and territorial governments are either developing or are in the process of implementing policies to address Canada's 9% national plastics recycling rate [2].

In November 2018, through the Canadian Council of Ministers of the Environment (CCME), the federal, provincial, and territorial governments approved in principle a Canada-Wide Strategy on Zero Plastic Waste [84], building on the global Ocean Plastics Charter that Canada advanced during its G7 presidency in 2018. Phase 1 and Phase 2 of the Canada-Wide Action Plan on Zero Plastic Waste were published through the CCME in 2019 and 2020, respectively.

In October 2020, the Government of Canada announced proposed next steps to achieve the goal of zero plastic waste by 2030. In May 2021, "plastic manufactured items" was added to Schedule 1 of the *Canadian Environmental Protection Act, 1999* (CEPA), enabling regulatory and other action in support of reaching Canada's zero plastic waste goal and setting the conditions for a plastics' circular economy. Proposed regulations are under development to ban or restrict certain single-use plastics and to establish recycled content requirements for plastic products.

There is also significant activity at the provincial level. As an example, in 2016 Ontario passed the Resource *Recovery and Circular Economy Act* (RRCEA) [3], which is the statutory basis by which extended producer responsibility (EPR) for the collection and management of end-of-life products and packaging is implemented. Proposed "Blue Box" regulations under the RRCEA will make individual producers whose products generate waste packaging and paper responsible for delivering residential recycling to Ontarians and meeting material-specific recycling targets.

Similarly, in March 2021, the Quebec National Assembly adopted Bill 65, which amends the *Environmental Quality Act,* as the basis to modernize the province's deposit-return system for beverage containers and to transition from producer-funded municipal delivery of residential recycling of paper and packaging to EPR.

In addition, Alberta [4] and New Brunswick have proposed to regulate EPR for residential recycling in addition to their existing requirements for producer-operated deposit-refund systems for beverage containers.

Across Canada, EPR is becoming the default policy mechanism to address post-consumer waste associated with products and packaging. EPR assigns the property rights for end-of-life waste products and packaging to producers of the products and packaging that generate waste and holds the producers responsible for meeting regulatory performance standards such as recycling targets.

Accordingly, through the Canadian Council of Ministers of the Environment (CCME), provinces and territories are developing a roadmap for harmonizing EPR [5] to facilitate producer delivery of EPR against common regulatory standards and definitions.

One of the key definitions in question is that of recycling.

1.2 Lack of a Relevant Definition of Recycling

Currently, there is no consistent definition of recycling in Canada [6] or among the North American jurisdictions reviewed as part of this research study.

As context, EPR has been used as a policy tool for less than 30 years, a relatively brief period in the history of waste management. Producer responsibility was first introduced in the European Union (EU) in 1991 with the German Packaging Ordinance [7] followed in 1994 by the EU's Packaging and Packaging Waste Directive [8].

Producer responsibility was first utilized as a policy tool in Canada in 1994, but was not broadly utilized until the first decade of the 21st century with the adoption of *Ontario's Waste Diversion Act* in 2002 [9] and British Columbia's Recycling Regulation in 2004 [10].

At the time, the use of EPR (or product stewardship by which producers funded existing recycling systems) was primarily focused on diverting material from landfill rather than defining recycling formally.

Due to provincial policymakers' lack of experience with producer responsibility and limited technical depth with material management systems, they chose to utilize narrowly scoped regulations that relied on producers and their producer responsibility organizations to prepare plans describing their proposed approach to comply with the regulation for government review and approval.

While this approach provided an opportunity for provincial policymakers to learn about material management systems, it left the choice of terminology and definitions of the chosen terminology to regulated producers.

As discussed below, over time, policymakers have come to understand that the ability to enforce performance depends on precisely defined language and measurement methodologies.

1.3 The Purpose of Defining Recycling

Where policymakers require materials to be recycled or where there is a claim that a product or material is recycled (e.g., as criteria for public procurement of goods and services), there must be a common definition of recycling as a benchmark for determining its achievement. The fundamental question is how to define recycling as it pertains to plastics so that regulated persons and policymakers can measure progress towards addressing Canada's plastic waste problem.

Defining recycling is also critical to establishing recycling targets [11] under EPR. Setting such targets requires a clear and unambiguous definition of recycling for producers to verify they have achieved the targets in question. Specifically, a producer's recycling target is typically expressed as the weight of products, packaging, and materials recycled as a percentage of the weight of products, packaging, and materials supplied by that producer.

Current Canadian EPR policies and regulations define who is responsible for post-consumer waste (i.e., the producer) and the designated materials supplied into the respective jurisdiction. The critical outstanding question to regulate EPR effectively is what counts as recycled in the calculation of recycling performance. The definition of recycled essentially circumscribes the final disposition of products, packaging, and materials that may be included in the calculation of performance against the recycling target.

The definition of recycling also shapes where technological innovation and investment will occur as producers drive the development of technologies and systems to manage products, packaging, and materials to achieve regulatory compliance and meet commercial objectives.

If the definition of recycled is inconsistent with circular economy (CE) principles, then it can be expected that EPR supply chains will employ materials management solutions that are equally inconsistent with those principles. For example, if the definition allows for collected plastics to be sent for energy recovery (with the plastics converted to greenhouse gases and other pollutants), then we can expect the market will utilize energy recovery to manage plastics.

Where a standard is ill-defined or defined in a manner that does not maximize circularity, there will be less or misdirected technological development, innovation, and investment that could result in an undersupply of recycled plastics, polymers, monomers, and chemical carriers.

As noted by plastic recycling sector respondents to a survey as part of this study (see Section 2.1), a clear definition of recycling was deemed to be important to ensure clarity in recycling regulations, including meeting regulatory obligations as well as to support a level playing field so that unscrupulous producers cannot benefit commercially from false claims; to address sources of confusion by consistently measuring outcomes that contribute to a circular economy and exclude those outcomes that do not; and to support internal business operations to support economies of scale and investment in material sorting and recycling facilities.

Clearly defining recycling is critical to enabling the effective implementation of recycling targets under EPR in Canada. As such, a clear definition is of importance to both public policymakers that are seeking to achieve specific environmental outcomes and to the regulated community that must deliver them.

A clear definition of recycling is also of importance to the plastics recycling sector as it will determine what choices producers make in packaging design and manufacture, supply chain design, and infrastructure investments towards driving a circular economy for plastics in Canada.

1.4 Research Objectives

This research study is a follow-up to CSA Group's *A Roadmap to Support the Circularity and Recycling of Plastics in Canada – Technical Standards, Regulations and Research* [6]. Specifically, the report recommends the need to review existing standards or develop a new Canadian standard with definitions to support national recycling terminology. This includes adopting common definitions for recycling terminology to help ensure consistency at all levels of industry and government, consulting with governmental bodies to identify terminology and definitions required for regulatory action essentially providing a nationally harmonized set of terms consistently understood across all of Canada.

As such, the purpose of this research study is to propose a definition of recycling that could be used to develop a plastics recycling standard by meeting the following objectives:

- To increase the understanding of the physical science of recycling materials;
- To foster a deeper understanding of the specific processes and classification methods of plastics recycling;
- To assess the various definitions of recycling employed by Canadian and other leading jurisdictions and determine how changes to these definitions will support investments and innovations in plastic recycling supply chains and increase the use of post-consumer resin (PCR); and
- To inform policymakers and businesses as they make decisions to drive recycling and increase circularity.

2 Methodology

The research for this report was conducted by undertaking the following:

1. A scan of the scientific and technical literature to:
    a. Summarize the physical and chemical processes to make plastics;
    b. Develop a basis for understanding the energy and mechanical and/or chemical work required to recycle the chemical constituents of plastics;
    c. Summarize the various mechanical and chemical pathways and technologies for recycling plastics
    d. Collate existing definitions of recycling and concepts related to recycling of materials;
2. Evaluation of the mechanical and chemical pathways for recycling plastics identified in scientific and technical literature in the context of the concept of a plastics circular economy;

3. A jurisdictional scan of various definitions of recycling adopted by the EU, ten American states, and all Canadian provinces and territories; and
4. A questionnaire-based survey of the plastics value chain, including plastic resin manufacturers, plastic package manufacturers, producers of products using plastic packaging, material recycling facility (MRF) operators, secondary processors (i.e., mechanical and chemical recyclers) and trade associations representing these respective groups. The Canada Plastic Pact distributed the survey to its members and collated their response on behalf of the study team. The survey questionnaire can be found in Appendix A.

2.1 The Importance of Defining Recycling to Survey Respondents

A total of 19 stakeholders responded to the survey with representation as follows: brand-owners using plastic packaging (11), plastic sorter/primary processor (1), recycled plastic secondary processors (5), resin supplier (1), packaging supplier (1), and producer responsibility organization (1).

The majority of survey respondents place great importance on the definition of recycling. Respondents have widely varying pre-existing conceptions about its practical definition and varying interpretations of recycling-related nomenclature (e.g., closed-loop recycling, open-loop recycling, upcycling, and downcycling). A clear definition of recycling was deemed to be important to ensure clarity in recycling regulations, including meeting regulatory obligations as well as to support a level playing field so that unscrupulous producers cannot benefit commercially from false claims; to address sources of confusion by consistently measuring outcomes that contribute to a circular economy and exclude those outcomes that do not; and to support internal business operations to support economies of scale and investment in material sorting and recycling facilities.

The survey was also used to solicit comments from respondents regarding a preliminary definition of recycling, which was developed after the early research work: “Where materials are collected and processed in such a manner that they can be used in manufacturing to displace demand for the same raw materials produced from virgin sources.” Eighteen of 20 responses (90%) to the proposed definition were positive, though refinements were made to the definition contained in this report based on feedback received throughout the course of this research.

Additional key survey responses are interspersed in relevant sections of this report.

3 Making and Recycling Plastics

3.1 Raw Materials, Energy, and Waste of Making and Using Plastics

Plastics – polyethylene, polypropylene, polystyrene, etc. – are highly ordered molecules not found in nature. They are created by using energy (primarily from fossil resources) to reform base hydrocarbons found in oil and natural gas as well as other elements[1] into monomers (single-unit molecular building blocks) and polymers (chain-like structures made of single-unit molecular plastic building blocks).

The creation of polymers using primary or raw materials and energy turns simple chemical building blocks into complex polymers but generates pollution and lost heat in the process.

Other chemicals are added to polymers to give the resulting plastic resin (“plastic”) its specific physical properties. Where several different plastics and additives are used for the various components of a product or package, the increased complexity of the product or package can make their later separation back into constituent plastics and polymers more difficult, requiring more energy to do the chemical work[2]. Conversely, there are additives that can enhance the recyclability of plastics reducing the amount of energy required to recycle plastics, but these typically come with higher upfront manufacturing costs.

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[1] For example, hydrocarbons can be combined with fluorine to make fluoropolymers such as polytetrafluoroethylene used in non-stick cookware – a molecule that does not naturally occur in any appreciable quantity in nature.

[2] “Work” is the transfer of energy to or from a system by any means other than heat.

Plastics may also be produced from biological sources (typically plant-based biomass). These can be manufactured as either biodegradable plastics (broken down by the action of bacteria or other living organisms) or as "drop-in" substitutes for fossil-based plastics such as PET. These bio-based fossil plastic substitutes can be recycled in conventional recycling systems for fossil-based plastics.

Following manufacturing, markets distribute products and their packaging for consumption by millions of consumers. The distribution itself results in dissipated heat and pollution from fossil fuel combustion for transportation. After use, plastic products and packaging become waste.

Recovering products and packaging from consumers for recycling requires an expenditure of energy causing more pollution and dissipated heat.

Once recovered from consumers, products and packaging must be managed in a manner whereby the products or packages themselves or the constituent materials within them can be used again. This management – reuse and/or recycling – requires work that is driven by additional inputs of energy.

3.2 Objective of Recycling Plastics

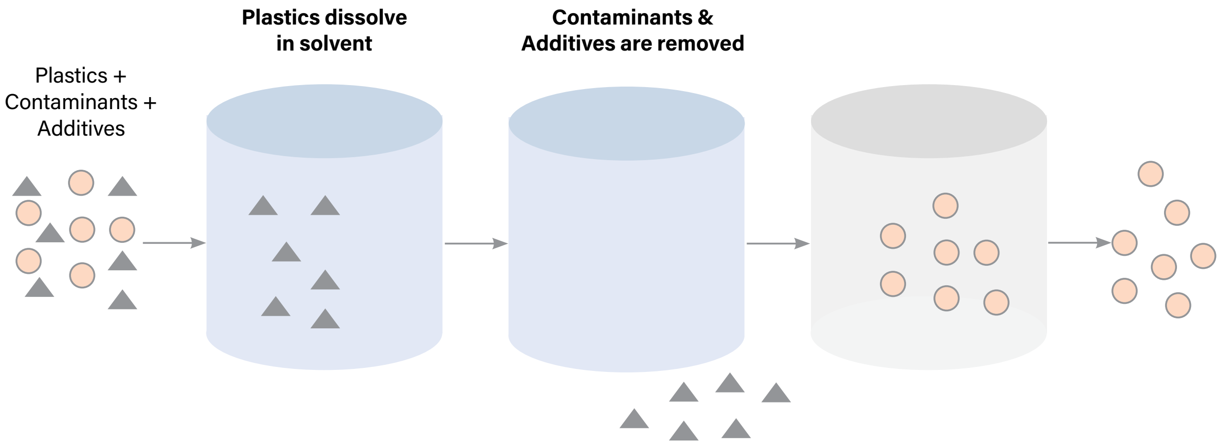
Thermodynamics is a branch of physics that deals with energy, work (i.e., transfer of energy to or from a system), temperature, and the physical properties of matter. Entropy is a thermodynamic concept that can be loosely described as the state of dissipation and diffusion of matter and energy in a system. A dissipative wasteful system results in greater entropy than a system that is highly structured and ordered (less entropy) [12].

The life cycle of plastics is a narrative about the increases and decreases of entropy and the role that recycling can play if it is defined in a manner that makes reducing entropy its objective.

Fundamentally, when we try to reuse and/or recycle plastic, we are trying to minimize entropy. As such, the objective of recycling plastics is to reclaim primary or raw materials (typically fossil resources) and avoid the waste (e.g., greenhouse gases, other air pollutants, effluents) associated with its production from primary or raw materials (resources) while minimizing how much of the same wastes are generated in undertaking that reclamation.

Figure 1 depicts how contaminated plastic that contains various performance additives (high entropy) is passed through a process to remove those contaminants and additives and "break down polymers into individual monomers or other hydrocarbon products" [13] that can then serve as building blocks or feedstock to produce polymers (low entropy). This process of chemical recycling requires inputs of energy to drive the chemical work of recovering monomers from contaminated mixed plastics.

Figure 1: Recycling: From high entropy to low entropy



This concept applied to a plastic beverage bottle translates as follows:

- The bottle may be "reused," that is, washed and refilled, which avoids the need to reconstitute the plastic in the bottle through recycling; or,
- The bottle may be "recycled" to reconstitute the plastic in the bottle either mechanically (through grinding and extruding into pellets) or chemically to recover constituent molecules in the plastic (polymers, monomers, or constituent chemical building blocks such as hydrogen and carbon monoxide) as feedstock to produce products and packaging.

More effort (energy) is required to return constituent plastics into a form suitable to meet market specifications for plastics as the complexity of the bottle in terms of the admixture of resins in closures, labels, and the bottle body increases.

This is further exacerbated by the complexity of other plastic packaging and products that may be processed in the same recycling stream as the bottle.

Currently our production use and end-of-life management of plastic is highly wasteful (entropic). Reducing the entropy of waste plastics requires inputs of energy to do the work to reclaim plastics or its molecular constituents. Currently, the bulk of the energy expended to recycle plastics is also derived from fossil resources. The implication of this is that some recycling practices that are highly energy intensive may provide no, or only marginal, greenhouse gas benefits over producing plastics from virgin materials[3].

Conversely, in nature both production and recycling are driven by sunlight. Sunlight is the reason that over time simple chemical building blocks found commonly in nature have organized themselves into the complex, information-rich structures that are living things[4]. It is also the fuel that powers the biological systems that break those structures down at their end-of-life into nutrients for the next cycle of life.

3.3 Nature's Plastic and Recycling of Carbon

Nature produces a form of plastic that we know as wood[5]. Wood is comprised of long-chain organic hydrocarbons – cellulose and lignin – which plants produce by chemically converting water, carbon dioxide, and minerals using sunlight through a process called photosynthesis.

At the end of a tree's life, it is recycled by bacteria and fungus that consume it and thereby make the hydrocarbons and minerals contained in its wood available for the next cycle of production.

Nature maintains this carbon balance by recycling carbon using solar energy. When fossil resources are extracted from the earth and converted into plastics using fossil energy and then combusted or disposed of, nature's carbon balance is upset. This is because the fossil resources consumed today are the complex hydrocarbons contained in plants and animals that were "sequestered" tens of millions of years ago in sediment. The process of plants drawing carbon dioxide out of the atmosphere using photosynthesis and sequestering some of those hydrocarbons in the earth as dead plants and animals (respectively contained in coal and oil and natural gas) gave us the atmosphere we had prior to the industrial revolution.

Sometime in the future it will be commercially viable to convert carbon dioxide and water into plastics such as polyethylene using sunlight [11]. Were plastics to be made through such synthetic photosynthesis and then recycled at end-of-use using solar energy, plastics would be transformed from a source of greenhouse gases to a means to reduce them (i.e., plastics would become a carbon sink).

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[3] This is partly due to the fact that plastics are not currently produced with recycling in mind. Plastic resin design and choice can mitigate the amount of energy needed to recycle them.

[4] Consider DNA that uses hydrocarbons to code the genetic information for the development, functioning, growth, and reproduction of life. DNA is both highly ordered and information rich. DNA is the product of billions of years of the sun's energy driving matter to organize itself into more complex structures.

[5] Another example are polyhydroxyalkanoates, or PHAs, which are polyesters produced in nature by microorganisms, including through bacterial fermentation of sugars or lipids (hydrocarbons like fats and waxes that are not water soluble).

"It is estimated that in the US, switching to renewable energy to produce plastics would cut plastic-related GHG emissions associated with the plastics economy by 50% to 75%" [14]. As such, using more renewable energy to power the production of fossil-based plastics and the recycling of plastics offers a way to dramatically mitigate the current carbon imbalance associated with plastics.

Reusing and recycling plastics involve the reclamation of plastics (as reusable components or packages, polymers, monomers, or constituent chemical building blocks) in order to displace the use of primary or raw materials in the production of plastics.

Various recycling methods and technologies are not the same in terms of what they produce (i.e., polymers, monomers or constituent chemical building blocks) and how effective they are (how much of what is processed is returned as recycled material).

4 The Evolution of the Definition of Recycling

In the last decade, there has been an emerging understanding that not only are the bulk of plastics supplied to markets as a product or packaging not collected but also that, of what is collected, only a portion is currently recycled in a manner that displaces fossil resources in the production of plastics [2]. As an example, Canada only recycled 12% of the plastic packaging used in 2019 [15].

Of what is collected, plastics are lost when they are contaminated with other materials, because of incomplete sorting (where mixed plastics contaminate each other limiting their use in manufacturing) and through process losses during recycling.

A lexicon has developed to capture this mass-balance reality of collecting, sorting, and processing materials in recycling supply chains. Some of these terms are briefly reviewed below with a focus on how the language describing recycling is evolving to include a more holistic view of the material and the energy considerations associated with recycling.

4.1 Sustainable Materials Management (SMM)

The Organisation for Economic Co-operation and Development (OECD) has established a definition of recycling under the concept of Sustainable Materials Management (SMM). SMM is built on conventions and definitions of functional and non-functional recycling in the context of material life cycles [16].

Much of the early work to develop SMM focused on the efficacy of recycling systems for metals. Under SMM, a life cycle for a given material is considered closed if it is recycled in a manner that displaces the raw materials in use [17]. Conversely, open material life cycles result when "EOL [end-of-life] products neither are collected for recycling nor enter those recycling streams that are capable of recycling the particular metal efficiently. Open life cycles occur as a result of products discarded to landfills, products recycled through inappropriate technologies (e.g., the informal sector[6] [18]) whereby metals are not or only inefficiently recovered, and metal recycling in which the functionality (i.e., the physical and chemical properties) of the EOL metal is lost" [17].

Emerging from the definitions of open and closed life cycles are the definitions of functional and non-functional recycling. Functional recycling results in a closed life cycle whereby a material is returned as raw material input for production. Conversely, non-functional recycling results in open life cycles whereby the material is itself not lost but its function as a replacement for virgin materials is lost typically through contamination by other materials.

These concepts that were originally developed to describe the material life cycles of metals are readily applicable to plastics.

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[6] The informal sector is characterised by small-scale, labour-intensive, largely unregulated and unregistered, low-technology manufacturing or provision of services" [18].

4.2 Closed-Loop and Open-Loop, Upcycling and Downcycling

The concepts of functional and non-functional recycling are often expressed using other terms that attempt to make them relatable to experiences in recycling systems.

These terms are interpreted varyingly and are a source of confusion to both public policymakers as well as to market actors in the plastic packaging value chain with the terms closed-loop and open-loop and downcycling and upcycling used with varying meaning often in context of survey respondents' role in the plastic packaging life cycle. These terms and their most common interpretations include [19]-[21]:

- **Closed-loop recycling:** Where plastics, polymers, monomers, or chemical building blocks are reutilized to displace the same plastic, polymer, monomer, or chemical building block produced from virgin resources (e.g., recycling of low density polyethylene – LDPE – in plastic bags to LDPE food containers).
- **Open-loop recycling:** Where plastics, polymers, monomers, or chemical building blocks are reutilized for a purpose other than what they were created for with the potential (but not necessarily) that they may not be subsequently reintroduced into a system that would recycle them (e.g., LDPE plastic bags to a plastic lumber park bench).

As shown in Figure 2, if the plastic lumber park bench will not, or cannot, be recycled to recirculate plastic, polymers, monomers, or chemical building blocks, it is then considered to be:

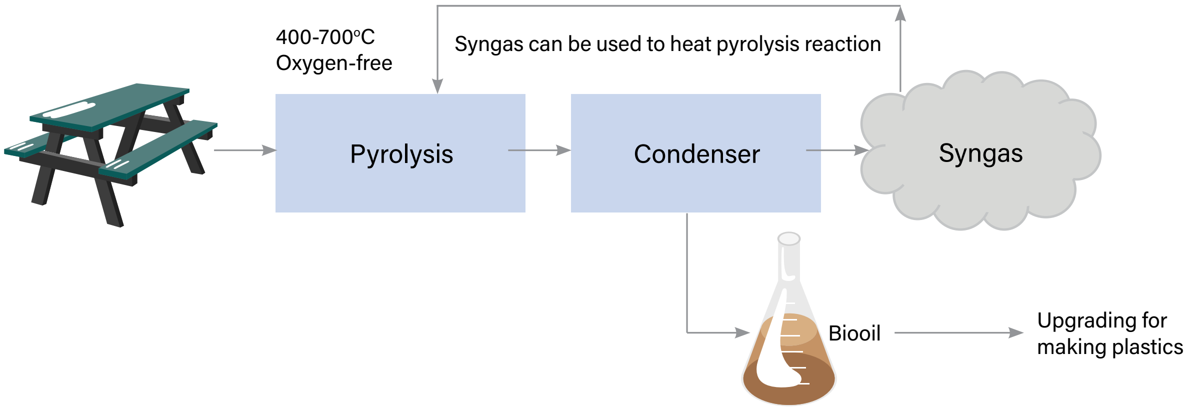
- **Downcycling:** Open-loop recycling of a material such that it is practically unrecoverable for the original purpose it was created. This puts plastic into a high entropy (more disordered) state that is difficult to recover, which means the downcycled plastic must be replaced with more virgin plastic made from fossil resources.
- **Upcycling:** Conversely, upcycling pulls materials that are in downcycled applications back into closed-loop systems. As an example, chemically recycling the park bench to recover plastic chemical building blocks for rebuilding monomers and polymers. However, this might require significant inputs of energy (which generates further emissions if it is derived from fossil resources).

4.3 Circular Economy (CE) and Recycling

While coined in 1988 [22], the term circular economy (CE) has been refined in the last 15 years as a unified conceptual framework for addressing the issues of resource consumption, energy use, and waste.

The focus on CE has been driven by the imperatives of resource scarcity (primarily of rare earth metals), energy use as it pertains to reliance on fossil resources with attendant greenhouse gas emissions (GHG), waste, and pollution, and wealth inequalities associated with global trade predicated on the linear use of resources [23].

Figure 2: Upcycling a plastic lumber bench requires energy



> "The term circular economy (CE) has been refined in the last 15 years as a unified conceptual framework for addressing the issues of resource consumption, energy use, and waste."

While CE draws its ideas from several earlier conceptualizations of circular systems (e.g., industrial ecology, biomimicry, and regenerative design [24]), it draws most heavily from chemist Michael Braungart's and architect Bill McDonough's concept of cradle to cradle [25]. This framework is characterized by three principles obtained from nature:

1. **Everything is a resource for something else.** In nature, the "waste" of one system becomes food for another. Everything can be designed to be disassembled and safely returned to the soil as biological nutrients or re-utilized as high-quality materials for new products as technical nutrients without contamination [without pollution by-products].
2. **Nature uses clean and renewable energy.** Living things thrive on the energy of current solar income. Similarly, human constructs can utilize clean and renewable energy in many forms –such as solar, wind, geothermal, gravitational energy and other energy systems being developed today – thereby capitalizing on these abundant resources while supporting human and environmental health.
3. **Celebrate diversity.** Around the world, geology, hydrology, photosynthesis and nutrient cycling, adapted to locale, yield an astonishing diversity of natural and cultural life. Designs that respond to the challenges and opportunities offered by each place fit elegantly and effectively into their own niches. [25]

Building on the McDonough-Braungart framing of cradle to cradle, the Ellen MacArthur Foundation (EMF) distills CE into three principles:

1. **Design out waste and pollution** which involves the redesign of products, packaging, and services to eliminate "impacts of economic activity that cause damage to human health and natural systems. This includes the release of greenhouse gases and hazardous substances, the pollution of air, land, and water."
2. **Keep products and materials in use** to "preserve value in the form of energy, labour, and materials. This means designing for durability, reuse, remanufacturing, and recycling to keep products, components, and materials circulating in the economy. Circular systems make effective use of bio-based materials by encouraging many different uses for them as they cycle between the economy and natural systems."
3. **Regenerate natural systems.** "A circular economy avoids the use of non-renewable resources and preserves or enhances renewable ones, for instance by returning valuable nutrients to the soil to support regeneration, or using renewable energy as opposed to relying on fossil fuels." [26]

EMF derives a definition of recycling plastics from these three principles as illustrated in Figure 3.

5 Mapping Recycling Technologies against the CE Conceptualization of Recycling

> The EMF circular economy conceptualization of fossil-based plastics recycling builds on the thermodynamic concepts of recycling discussed earlier whereby renewable energy is used to drive recycling loops that recycle polymers, monomers, and chemical building blocks towards displacing fossil resources in the production of plastics.

In the following section, current and nascent plastics recycling technologies are examined more closely in the context of the objective of driving a plastics CE by recycling plastics to displace fossil resources in the production of plastic.

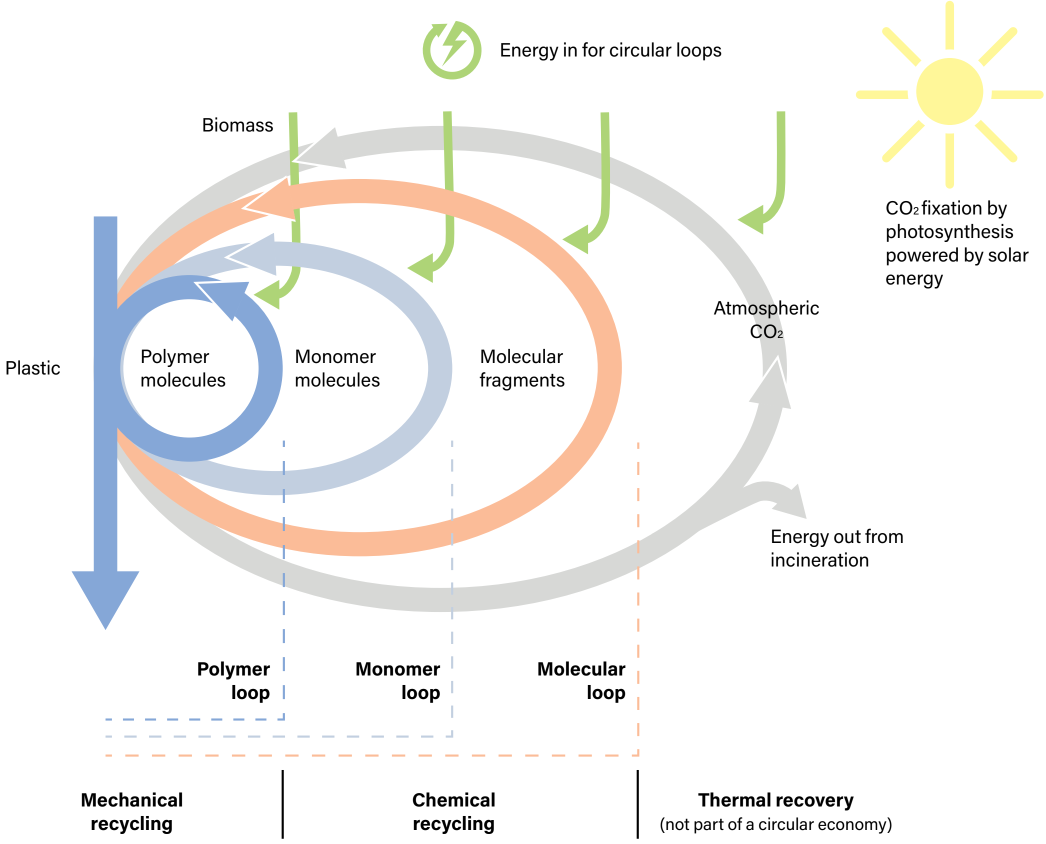
5.1 An Overview of Mechanical and Chemical Methods for Recycling Plastics

Plastics may be recycled through two primary methods: mechanical and chemical.

Mechanical methods involve: [19]

- **a.** Sorting and separating plastics by size, shape, and density;
- **b.** Baling, if the plastic is not being processed at the sorting site;
- **c.** Washing to remove organic contaminants;
- **d.** Grinding into flakes and pelletizing for easier processing; and
- **e.** Melting and reshaping the pellets.

Figure 3: Loops in a plastics circular economy. Image copyright © Ellen MacArthur Foundation (2019) [31].



Chemical methods comprise three generically described pathways [19], [27]-[29]:

- **Purification** is a process that involves dissolving plastic in a solvent, then separating and purifying the mixture to extract additives and dyes to ultimately obtain a "purified" plastic. The purification process does not change the polymer on a molecular level.
- **Decomposition** is a process that involves breaking down molecular bonds of the plastic to recover the simple molecules ("monomers") from which the plastic is made. Monomers may be single molecules or short fragments of molecules bound together called "oligomers", both of which are often reconstructed into plastics. This process, sometimes referred to as "depolymerization", can be biological, chemical, or thermal and, in some cases, a combination of two or three of these methods.
- **Conversion** is similar to decomposition in that the process involves breaking the molecular bonds of the plastic. A key difference is that the output products from conversion processes are often liquid or gaseous hydrocarbons similar to the products derived from petroleum refining. These raw materials may enter different supply chains, such as fuels for combustion, and/or petrochemicals (e.g., naphtha) that can be made into intermediates and monomers for new plastics. [30]

Each of the methods above is suited to a specific plastic or combination of plastics. The key considerations and challenges in their deployment are discussed in Appendix B.

5.2 Recycling Plastics: Practical Considerations

All the recycling methods described above have the potential to advance a circular economy for plastics to *varying degrees* by reclaiming plastics (as polymers, monomers or as its constituent chemical building blocks) to displace fossil resources in the production of plastics.

Irrespective of the recycling method chosen, there are several factors that affect the recyclability of plastics [31][7]:

- Is plastic collected for recycling or as mixed waste (e.g., single-stream recycling), and is it directed to a sorting facility or landfill (from which plastic could be later sorted and diverted)?
- Is the collected plastic feedstock a homogeneous "mono-plastic" or composed of a mix of polymers and other materials (e.g., a plastic composite with a metal foil layer)? The less homogenous the plastic, the less amenable it is to mechanical recycling. Plastics laminated with non-plastic materials pose significant barriers to recycling by any means.
- If the plastic feedstock is a heterogeneous mix of plastics, is its composition known?
- Is the plastic feedstock clean or contaminated? Will additional sorting and washing be required?

These factors determine which (if any) method of recycling is a viable option, and whether the plastic can be recycled to displace fossil resources in the manufacture of the original polymer (closed-loop) or in a manner where it cannot be used to displace fossil resources and must therefore be replaced in its original use with fossil resources (open-loop) [19].

It should be clear from the factors above that how plastic products and packaging are designed, collected, and sorted must be addressed to maximize the opportunities to utilize available recycling technologies to their fullest potential.

There is no one technological solution to recycling plastics – several recycling technologies may need to operate in parallel, receiving feedstocks of collected plastics that have been properly sorted and voided of contaminants in a manner suitable for their respective mechanical or chemical processes.

However, even where a recycling technology receives an optimal stream of sorted feedstock, each recycling method then has unique performance characteristics

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[7] "Many substances are used in combination with others, like chemical additives and plastic composites, and are therefore not easily separable from each other. This leads to impurities in the recycled material if using the mechanical recycling route, and therefore limits material quality in further usage. Moreover, when products move through the value chain, there is additional mixing and contamination of materials, making it economically unfeasible to separate many materials even if they are physically and chemically distinguishable" [31].

that dictate how closely it operates to the CE conception of recycling as discussed in Section 4.3. These characteristics include process inputs and process outputs.

Process inputs include material inputs (i.e., catalysts, solvents, additives) and the energy by source used to power the recycling process and its overall greenhouse gas and air emissions footprint. Again, consistent with CE principles discussed in Section 4.3, where the inputs of energy into recycling systems are renewable, then the energy-related concerns about greenhouse gas emissions associated with energy consumption are mitigated. However, where recycling processes are powered by fossil-based energy or by the conversion of a portion of the virgin plastic feedstock as process fuel, then the associated emissions need to be accounted for.

All plastics recycling methods and technologies can be evaluated within the framework of recycling as the reclamation of plastics (as polymers and monomers or as its constituent chemical building blocks) to displace primary or raw materials in the production of plastics.

Where chemical recycling technologies are applied, only the portion of the chemical carrier outputs that are destined to displace fossil resources in the production of plastics are considered recycled.

Process outputs include the yield of fuels that may be combusted to power the recycling process itself or marketed as a product, the residual wastes and effluents, and the yield of recycled materials (i.e., those that will displace fossil resources in the production of plastics). “Recycling efficiency” is the amount of recycled polymers, monomers, or constituent chemical building blocks output by the recycling process that displace fossil resources in the production of plastics as a percentage of the total amount of plastic feedstock input into the recycling process.

While the yield of recycled materials is of interest in terms of calculating what is recycled, all material and energy inputs and outputs to a given recycling process need to be measured to fully describe its gate-to-gate profile and effectiveness. When accounting for recycling yield, complexity arises from chemical recycling pathways, specifically when the outputs of the recycling process are chemical “carriers” such as ethanol and methanol that can be used alternatively as feedstocks to produce either fuels or plastics, and when the chemical carriers output from recycling processes may be mixed with chemical carriers produced from fossils resources in distribution systems.

In these situations, methods to verify chain-of-custody such as mass balance protocols have been developed to allocate the mass balance of plastic inputs into a recycling process to the recycled material outputs that displace fossil resources in the production of plastics [31].

To be consistent with the CE principles discussed earlier, only the portion of the carrier that is destined to produce plastics is counted as recycled.

6 Common Recycling Definitions Used in North America and European Legislation

Policy definitions of the following terms were identified in statute, regulation, or other public policy instruments: recycle or recycling; recover or recovery; and composting or organic recycling.

The following jurisdictions for which the identification was undertaken include all ten Canadian provinces and three territories, the EU, and ten American states: California, Connecticut, Maine, Maryland, Minnesota, New York, Oregon, Rhode Island, Vermont, and Washington. These states were chosen because they have more producer responsibility laws and therefore were likely to have updated policies on recycling and/or composting (i.e., recycling of organic materials).

6.1 Canadian Provinces Where Key Regulatory Definitions Are Not in Statute or Regulation

Where key terms such as “recycling”, “recovery”, or “composting” have not been defined in legislation or regulation, some provinces have delegated responsibility to define regulatory language to another agency.

For instance, in Alberta, the Beverage Container Management Board, which has regulatory responsibility for registering beverage containers, is authorized to approve recycling methods for purposes of managing approved beverage containers. The producer-operated Alberta Management Recycling Authority is authorized to make bylaws respecting agreements concerning processing and recycling of designated materials.

In New Brunswick, the Tire Stewardship Board may adopt the standards it considers appropriate in relation to the recycling and processing of tires.

In Newfoundland and Labrador, the Multi-Material Stewardship Board is authorized to establish standards relating to the recycling, processing, and other handling of designated materials.

In the Northwest Territories, the Chief Environmental Protection Officer has regulatory authority to impose terms or conditions respecting processing and recycling of designated materials.

6.2 Definitions in Current Usage

6.2.1 Definition of Recycle

While the words “recycle” and “recycling” are commonly used in legislation and policies across Canada, the term was defined in only three provinces: Manitoba, Prince Edward Island, and Newfoundland and Labrador. The table below sets out definitions of recycle currently used in these Canadian provinces, the EU, and in California, Connecticut, Maine, Maryland, Minnesota, New York, Oregon, Rhode Island, Vermont, and Washington. A definition of recycle was not located in legislation or policies adopted by Canadian provinces and territories that are not listed in Table 1.

Across jurisdictions, the definitions of recycle have some common features. First, the material to which the word is applied is post-use and considered waste because it has been discarded by the user. Second, the objective of the recycling process is to transform or reprocess the material for a future use, and third, the use does not include disposal on land or the destruction of recyclable materials in a manner that precludes further use which, in most jurisdictions, includes thermal destruction of the material by burning or energy recovery[8] [83].

However, the definitions of recycle vary in that they can incorporate terms referring to energy recovery that describe burning of materials as fuels to generate heat steam or electricity generation or the steps in the process leading to the transformation of materials (e.g., collecting, transporting, handling, storing, disassembling, dismantling, sorting, separating, shredding, processing, and remanufacturing).

6.2.1.1 EU Rules for the Calculation, Verification, and Reporting of Data on Waste

Recognizing that the definition of recycle was insufficient to support implementation of the Packaging and Packaging Waste Directive, the EU adopted an “implementing decision” in 2019 [32], which sets forth several definitions to calculate recycling rates under EPR for packaging:

- “Targeted materials” means packaging waste materials that are recycled into products, materials or substances that are not waste.

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[8] Despite the material being destroyed through combustion, Nova Scotia has specifically excluded incinerators in its definition of a thermal treatment facility : “…means a facility for the thermal treatment of waste to produce liquid or gaseous fuels or energy but does not include an incinerator”. Quebec’s guidance for the *Environmental Protection Act* describes “thermal destruction of residual materials as constituting energy conversion insofar as the processing of the materials respects the regulatory standards prescribed by the Government, including a positive energy assessment and the minimum energy efficiency required, and contributes to the reduction of greenhouse gas emissions”.

"Recognizing that the definition of recycle was insufficient to support implementation of the Packaging and Packaging Waste Directive, the EU adopted an "implementing decision" in 2019, which sets forth several definitions to calculate recycling rates under EPR for packaging."

- "Non-targeted materials" are waste materials that are not recycled into products, materials, or substances.
- "Preliminary treatment" means any treatment operation that packaging waste materials undergo before submission to the recycling operation whereby those materials are recycled. This includes checking, sorting, and other preparatory operations to remove non-targeted materials and to ensure high-quality recycling.
- "Calculation point" is the point where packaging waste materials enter the recycling operation whereby waste is recycled or where waste materials are no longer a waste in preparation for being recycled.
- "Measurement point" means the point where the mass of waste materials is measured with a view to determining the amount of waste recycled at the calculation point.
- Rules for reporting data to calculating recycling rates; as for example:
  - Packaging made of different materials which cannot be separated by hand are to be reported under the predominant material by weight (if the package is mostly plastic by weight, it is reported as plastic).
  - The amount claimed as recycled is the amount sent to an effective recovery or recycling process (measured as an input to that process and not an output).
  - If the output of a material recycling facility is sent to effective recycling or recovery processes without significant losses, it is considered recycled.

Any definition of recycling must adopt similar rules for its practical application, which will be discussed in Section 7.

6.2.1.2 Ontario's Definition of "Management of Collected Materials"

While *Ontario's Resource Recovery and Circular Economy Act 2016* (RRCEA) [3] does not specifically define the word recycling, it prescribes activities that define when a material can be deemed recycled: "used in the making of new products, packaging or other things, or used as a nutrient for improving the quality of soil, agriculture or landscaping".

Regulations for batteries [33] and tires [34] as promulgated under the RRCEA set forth specific requirements for what outputs from recycling processes are consistent with the general definition set forth in the RRCEA.

6.2.1.3 Definitions of Recycle Used in Other Jurisdictions

Table 1: Definitions of Recycle Used by Canadian Provinces, the European Union, and Ten American States

Definitions of Recycle		
Canada	**Manitoba – *The Waste Reduction and Prevention Act*** [35]	To do anything, including reuse or recover, that results in providing a use for a thing that otherwise would be disposed of or dealt with as waste, including collecting, transporting, handling, storing, sorting, separating, and processing the thing, but does not include the disposal of waste in land, the use of a thermal destruction process or any other activity prescribed by regulation.
	Prince Edward Island – *Environmental Protection Act* [36]	The practice of accepting, collecting, storing, sorting, handling, and preparing for transport or transporting, recyclable material for the purpose of the use or incorporation of the material in the manufacture of secondary products, and includes (i) compacting, (ii) bundling, (iii) baling, (iv) shredding, and (v) crushing.
	Newfoundland and Labrador – *Environmental Protection Act* [37]	A process by which a post-use material is collected with the intent of processing that material to transform it into another material or substance or for another use.
European Union	**Packaging and Packaging Waste Framework Directive** [8]	To do anything, including reuse or recover, that results in providing a use for a thing that otherwise would be disposed of or dealt with as waste, including collecting, transporting, handling, storing, sorting, separating, and processing the thing, but does not include the disposal of waste in land, the use of a thermal destruction process or any other activity prescribed by regulation.
	Batteries [38]**, End-of-Life Vehicles** [39]**, and WEEE Directives** [40]	The reprocessing in a production process of waste materials for their original purpose or for other purposes, but excluding energy recovery.
	Packaging and Packaging Waste Directive [8]	The reprocessing in a production process of the waste materials for the original purpose or for other purposes, including organic recycling but excluding energy recovery.
California	***Resource Conservation and Recovery Act*** [41]	The process by which recovered materials are transformed into new products.
	Beverage Container Recycling & Litter Reduction Act [42]	The reuse or refilling of empty beverage containers, or the process of sorting, cleansing, treating, and reconstituting empty post-filled beverage containers for the purpose of using the altered form; does not include merely sorting, shredding, stripping, compressing, storing, landfilling, or disposing of an empty beverage container.
Connecticut	**Glossary of Recycling and Waste** [43]	*Recycle* – Minimizing waste generation by recovering and reprocessing usable products that might otherwise become waste. *Recycling* – The processing of solid waste to reclaim material therefrom.
	Senate Bill No. 828 Public Act No. 11-24 An Act Establishing a Paint Stewardship Program [44]	"*Recycling*" means any process by which discarded products, components, and by-products are transformed into new, usable, or marketable materials in a manner in which the original products may lose their identity. "Recycling" does not include energy recovery.

Definitions of Recycle		
Maine	**Title 38: Chapter 13 Waste Management** [45]	The collection, separation, recovery, and sale or reuse of materials that would otherwise be disposed of or processed as waste or the mechanized separation and treatment of waste, other than through combustion, and the creation and recovery of reusable materials other than as a fuel for the generation of electricity.
	Stewardship Program for Architectural Paint [46]	Any process by which discarded products, components, and by-products are transformed into new, usable, or marketable materials in a manner in which the original products may lose their identity but does not include energy recovery or energy generation by means of combusting discarded products, components, and by-products with or without other waste products.
	Stewardship Program for Electronic Waste [47]	The use of materials contained in previously manufactured goods as feedstock for new products, but not for energy recovery or energy generation by means of combustion.
Maryland	**Maryland Code Environment Section 9-1701** [48]	"*Recycling*" means any process in which materials that would otherwise become solid waste are collected, separated, or processed and returned to the marketplace in the form of raw materials or products. "*Recycling*" includes composting.
Minnesota	***Waste Management Act* Chapter 115A Section 115A.03 Definitions** [49]	"*Recycling*" means the process of collecting and preparing recyclable materials and reusing the materials in their original form or using them in manufacturing processes that do not cause the destruction of recyclable materials in a manner that precludes further use.
New York	**Title 19 Waste Tire Management and Recycling Section 27-1901** [50]	7. "*Recycle*" means to use recyclables in manufacturing a product for an end use other than burning for recovery of useable energy.
	Title 20 Postconsumer Paint Collection Program Section 27-2001 [51]	8. "*Recycling*" means a process by which discarded products, components, and by-products are transformed into new usable or marketable materials in a manner in which the original products may lose their identity. This term excludes thermal treatment or the use of postconsumer paint as a fuel substitute or for energy production.
	Title 26 Electronic Equipment Recycling and Reuse Section 27-2601 [52]	15. "Recycle" means to separate, dismantle, or process the materials, components or commodities contained in electronic waste for the purpose of preparing the materials, components, or commodities for use or reuse in new products or components thereof, but not for energy recovery or energy generation by means of combustion, gasification, pyrolysis, or other means. Recycling includes the manual and mechanical separation of electronic waste to recover materials, components, or commodities contained therein for the purpose of reuse or recycling, and changing the physical or chemical composition of electronic waste to segregate components for purposes of recycling those components.
Oregon	***Reuse and Recycling Act*** [53]	Processing through disassembling, dismantling, shredding, transforming, or remanufacturing covered electronic devices, components, and by-products into usable or marketable raw materials or products in a manner such that the original products may lose their identity; or smelting materials from components removed from covered electronic devices to recover metals for reuse in conformance with applicable laws and rules; does not include: (A) landfill disposal or incineration of covered electronic devices; or (B) energy recovery or energy generation by means of combusting covered electronic devices, components, and by-products with or without other waste.
	Architectural Paint Stewardship Program ORS 459A.822 Definitions [54]	Any process by which discarded products, components, and by-products are transformed into new usable or marketable materials in a manner in which the products may lose their original composition.

Definitions of Recycle		
Rhode Island	**Rules and Regulations for Solid Waste Management Facilities and Organic Waste Management Facilities (250-RICR-140-05-1)** [55]	160. "*Recycling*" means the reuse or remanufacture of recovered resources in manufacturing, agriculture, power production, or other processes.
Vermont	**No. 148. An Act Relating to Establishing Universal Recycling of Solid Waste** [56]	(27) "*Closed-loop recycling*" means a system in which a product made from one type of material is reclaimed and reused in the production process or the manufacturing of a new or separate product.
Washington	**Senate Bill 5022 An Act Relating to the Management of Certain Materials to Support Recycling and Waste and Litter Reduction** [57]	(23) "*Recyclable*" means a covered product that is regularly collected, separated, and reprocessed into a recycled material, and that does not contain harmful chemical, physical, biological, or radiological substances that will pose a threat to human health or the environment for its intended or likely manner of use. (24) (a) "*Recycled material*" means material derived from covered products that is reprocessed into products or commodities used in the production of new products whether for the original or another purpose. (b) "Recycled material" does not include energy recovery and the reprocessing of materials that are to be used as fuels or landfill cover.
	ISO 18604:2013 Packaging and the Environmnent – Material Recycling [58]	Reprocessing, by means of a manufacturing process, of a used 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.

6.2.2 Definition of Recovery

Table 2 sets out definitions of recovery currently used in six Canadian provinces, the EU, and five American states. A definition of recovery was not located in legislation or policies adopted by the other Canadian provinces and territories or in California, Maine, Oregon, Vermont, or Washington.

The definitions of recovery have some common features. The word is applied to things that might otherwise be waste or residual materials, and the objective of the recovery process is productive use, described as useful materials, valuable resources, a useful purpose, or useable materials, substances, or products.

The differences among the definitions of recovery are substantive. Some definitions refer to material collected while other definitions refer to material after processing. Some definitions include regeneration, biological treatment (including composting and biomethanation), and land farming as productive use while others do not include these management methods. Also, some definitions include energy such as steam and electricity while another definition excludes processes that constitute elimination while other definitions make no explicit reference to thermal destruction or energy recovery.

There are also differences among the definitions in the point of measurement of recovery. For instance, in British Columbia, performance is measured as recovery which is defined as the amount of product collected divided by the amount of product produced (i.e., reported as supplied by obligated producers), expressed as a percentage. In Saskatchewan, the point of measurement differs by approved program plan. As an example, in the Waste Packaging and Paper Program: recovery is calculated as a percentage with the numerator being the quantity of the designated material shipped to end-markets and the denominator being the quantity of the designated material supplied by obligated producers. Alternatively, in the Tire Stewardship Program: recovery is calculated as a percentage with the numerator being the total number of tires collected and the denominator being the number of new tires sold. On the other hand, in Manitoba, recovery performance is measured as the total amount of product collected as a percentage of the total amount of product supplied.

Table 2: Definitions of Recovery Used by Six Canadian Provinces, the European Union and Five American States

Definitions of Recovery		
Canada	**British Columbia** – ***Recycling Regulation*** [59]	The amount of product collected.
	Saskatchewan	**Waste Packaging and Paper Program** [60]: the amount of product shipped to end-markets. **Tire Stewardship Program** [61]: the amount of product collected.
	Manitoba – Guideline for Packaging and Printed Paper Stewardship: Recovery Rate [62]	The amount of product collected.
	Ontario – ***Resource Recovery and Circular Economy Act*** [63]	The extraction of useful materials or other resources from things that might otherwise be waste, including through reuse, recycling, reintegration, regeneration, or other activities [3].
	Quebec – ***Environment Quality Act*** [64]	Any operation to obtain usable substances or products, or energy, from residual materials through reuse, recycling, or biological treatment, including composting and biomethanation, land farming, regeneration, or any other process that does not constitute elimination.
	Newfoundland and Labrador – ***Environmental Protection Act*** **[37]**	The process of obtaining and reutilizing material or energy from solid, liquid, or gaseous waste.
European Union	**Packaging and Packaging Waste Directive** [8]	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.
Connecticut	**Glossary of Recycling and Waste** [43]	Usable recycled materials that have been removed from municipal solid waste.
Maryland	**Maryland Code Environment Section 9-1701** [65]	Does not define recovery but defines "*Resource recovery facility*" as a facility in existence as of January 1, 1988 that: (1) Processes solid waste to produce valuable resources, including steam, electricity, metals, or refuse-derived fuel; and (2) Achieves a volume reduction of at least 50 percent of its solid waste stream.
Minnesota	**Environmental Protection Chapter 115A Section 115A.03 Definitions** [49]	Does not define recovery but defines "Resource recovery" as the reclamation for sale, use, or reuse of materials, substances, energy, or other products contained within or derived from waste.
New York	**Title 7 Solid Waste Management and Resource Recovery Facilities Section 27-0701** [66]	6. "*Resource recovery*" means the separation, extraction, and recovery of useable materials, energy or heat from solid waste through source separation, recycling centers, or other programs, projects, or facilities.
Rhode Island	**Rhode Island Rules and Regulations for Solid Waste Management Facilities and Organic Waste Management Facilities (250-RICR-140-05-1)** [55]	72. "*Energy recovery*" means treatment by which energy is derived or extracted from solid waste. 171. "*Resource recovery*" means the processing of solid waste in such a way as to produce materials or energy which may be used in manufacturing, agriculture, and other processes.

6.2.3 Definition of Composting (and Organic Recycling)

Table 3 sets out definitions of composting currently used in three Canadian provinces and seven American states. A definition of composting was not located in legislation or policies adopted by the other Canadian provinces and territories or in California, Maine, or Vermont.

The EU does not use the term composting but does define the term "organic recycling". As organic recycling is the recycling of biological material into compost, the EU's definition for organic recycling is included in Table 3.

The definitions of composting have some common features. The material to which the word is applied is organic matter, the process involves decomposition by bacterial, microbial, or biological action under controlled conditions; and the output of the composting process is considered stable (i.e., requires no further processing).

The definitions of composting vary. Canadian definitions refer to humus, land application, or inert material while the EU's definition references both stabilized organic matter and methane.

Alternatively, Ontario's and Newfoundland and Labrador's definitions refer specifically to aerobic decomposition, Nova Scotia's definition refers to biological decomposition, which includes both aerobic and anaerobic decomposition, while the EU's definition of organic recycling includes both aerobic and anaerobic treatment. The New York definition includes use as animal feed or a feed ingredient, rendering, land application, composting, aerobic digestion, anaerobic digestion, fermentation, or ethanol production.

6.3 Definitions and Operational Outcomes

Across jurisdictions, differing definitions of key terminologies and tracking of performance against those definitions using differing measurement points and calculation methodologies has a significant impact on operational outcomes. The implications of differing definitions of recycle or recycling, recovery and composting are discussed below.

6.3.1 Definition of Recycling

The definition of recycling defines where recycling is measured. In practice, even where definitions include remanufacturing in the list of activities considered as recycling, tracking is typically from the point of collection through to the point of shipment from primary processing facilities, not to the locations where materials are used in manufacturing. Only recently, and only in a few instances, has there been any effort to verify recycled materials as having been sent to manufacturing [33].

In addition to differing definitions of key terminology among jurisdictions, tracking of performance against those definitions utilizes differing measurement points and calculation methodologies. The lack of a standard approach to tracking and measurement of performance results in datasets that cannot be integrated to assess a jurisdiction's progress against its policy objectives and that cannot be used to benchmark among jurisdictions.

There is no consistent definition of recycling in Canada. Many of the definitions in current usage include a long list of possible activities (e.g., collecting, transporting, handling, storing, disassembling, dismantling, sorting, separating, shredding, processing, remanufacturing) that create confusion about which step constitutes recycling and whether recycling has occurred at the completion of any step.

The EU's and Ontario's efforts to define recycling and institute supplemental definitions and measurement protocols are progressive steps towards establishing a practical definition of recycling that is consistent with CE principles.

6.3.2 Definition of Recovery

Recovery has a variety of meanings across jurisdictions (e.g., collection, resource recovery, as another term for recycling, materials shipped from processing facilities, and energy recovery). As noted in the survey responses, this word is a source of confusion in the industry. Even if this term were to have a common definition used by all Canadian jurisdictions at some point in the future, there is likely to be persistent confusion about the term.

Table 3: Definitions of Composting and Organic Recycling

Definitions of Composting Used by Three Canadian Provinces		
Canada	**Ontario[9] – Food and Organic Waste Policy Statement** [67]	Aerobic decomposition of organic matter by bacterial action for the production of stabilized humus.
	Nova Scotia – Solid Waste-Resource Management Regulations [68]	The biological decomposition of organic materials, substances, or objects under controlled circumstances to a condition sufficiently stable for nuisance-free storage and safe use in land applications..
	Newfoundland and Labrador – *Environmental Protection Act* [37]	The treatment of waste and organic matter by aerobic decomposition and microbial action to produce a stable, inert material.

Definition of Organic Recycling Used by the European Union		
European Union	**Packaging and Packaging Waste Directive** [8]	The aerobic (composting) or anaerobic (biomethanization) treatment, under controlled conditions and using micro-organisms, of the biodegradable parts of packaging waste, which produces stabilized organic residues or methane.

Definitions of Composting Used by Seven American States		
Connecticut	**Glossary of Recycling and Waste** [43]	A process of accelerated biological decomposition of organic material under controlled conditions.
Maryland	**Maryland Code Environment Section 9-1701** [65]	"*Composting*" means the controlled biological decomposition of organic waste material in accordance with the standards established by the Secretary under this title.
Minnesota	**Environmental Protection Chapter 115A Section 115A.03 Definitions** [49]	Controlled microbial degradation to yield a humus-like product meeting the agency's class I or class II, or equivalent, compost standards and where process rejects do not exceed 15 percent by weight of the total material delivered to the facility.
New York	**Title 22 Food Donation and Food Scraps Recycling Section 27-2201** [69]	3. "*Organics recycler*" means a facility, permitted by the department, that recycles food scraps through use as animal feed or a feed ingredient, rendering, land application, composting, aerobic digestion, anaerobic digestion, fermentation, or ethanol production. Animal scraps, food soiled paper, and post-consumer food scraps are prohibited for use as animal feed or as a feed ingredient. The proportion of the product created from food scraps by a composting or digestion facility, including a wastewater treatment plant that operates a digestion facility, or other treatment system, must be used in a beneficial manner as a soil amendment and shall not be disposed or incinerated.
Oregon	**459A.605 Rules for Purchase of Compost and Sewage Sludge by State** [70]	Compost means the product resulting from the controlled biological decomposition of organic wastes that are source separated from the municipal solid waste stream.

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9 Ontario’s Food and Organic Waste Policy Statement (released for consultation in September 2020) defines “anaerobic digestion” as the decomposition of organic matter by bacteria in an oxygen-limiting environment (as defined in Regulation 347 under the Environmental Protection Act).

Definitions of Composting Used by Seven American States

Rhode Island	**Rhode Island Rules and Regulations for Solid Waste Management Facilities and Organic Waste Management Facilities (250-RICR-140-05-1)** [55]	4. "*Aerated static pile composting*" means a method of composting in which oxygen and temperature levels are mechanically controlled by forced aeration using blowers. A series of perforated pipes (or equivalent) air distribution system runs underneath the compost pile and is connected to a blower that either draws or blows air through the pile. Little or no pile turning is performed. 7. "*Aerobic composting*" means decomposition of organic materials by bacteria in the presence of oxygen. 9. "*Agricultural composting*" means the composting of agricultural by-products and/or other specified compostable materials on an "agricultural unit," resulting in compost products for agricultural and horticultural uses. 14. "*Anaerobic digestion*" means decomposition of organic material in the absence of oxygen. 45. "*Composting*" means any aerobic, thermophilic process which allows for the conversion of raw organic materials into a stable soil amendment.
Washington	**Senate Bill 5022 An Act Relating to the Management of Certain Materials to Support Recycling and Waste and Litter Reduction** [57]	(4) "*Compostable*" means a covered product that is capable of undergoing aerobic biological decomposition in a system meeting the requirements of chapter 70A.205 RCW, that results in the material being broken down primarily into carbon dioxide, water, inorganic compounds, and biomass.
	Senate Bill 5286 An Act Relating to Establishing a Statewide Organic Waste Management Goal [71]	(3) "*Composted material*" means organic solid waste that has been subjected to controlled aerobic degradation at a solid waste facility in compliance with the requirements of this chapter. Natural decay of organic solid waste under uncontrolled conditions does not result in composted material.

Where governments use the term recovery, it should be clearly specified that it in no way connotes recycling as defined in this report. Clear examples differentiating recovery from recycling should be provided, for example, waste-to-energy, waste-to-fuel, co-firing (adding plastics to coal in steel-making), backfilling (plastic in roads), and so on.

6.3.3 Definition of Composting

The distinction between aerobic composting and anaerobic digestion as acceptable methods to recycle organic waste into biological nutrients in some definitions is constraining. The EU's definition of organic recycling, by including both aerobic composting and anaerobic digestion, avoids this drawback.

Consistent with CE principles, materials processed into biological nutrients through aerobic composting and anaerobic digestion should be deemed to have been subject to organic recycling.

7 Proposed Definition of Recycling

Plastics can be produced from both fossil resources and biomass. Fossil-based plastics may be manufactured to be mechanically and chemically recycled or to be biodegradable or organically recycled. Similarly, bio-based plastics may be manufactured to be "drop-in" replacements for fossil-based plastics and recycled in the same systems as fossil-based plastics, or they may be manufactured to be biodegradable or organically recycled.

The proposed definition below considers all of these plastics production options and end-of-life pathways.

Consistent with CE principles, the following working definition of recycling is proposed:

> *Recycling is the reclamation of materials in such a manner that they can be used to displace the primary or raw materials they were produced from.*

In the context of plastics, and given the technology discussion covered above, this definition can be stated as:

> *Recycling is the reclamation of plastics (as polymer, monomer, or constituent chemical building blocks) in such a manner that they displace the primary or raw materials that are used as chemical building blocks in the production of plastics and plastic products and packaging.*

In the context of non-fossil, bio-based plastics and consistent with CE principles, this definition can be stated as:

> *Organic recycling is the processing of bio-based plastics into biological nutrients.*

Of note, where fossil-based plastics are manufactured to be biodegradable and the products of that degradation result in a net loading of greenhouse gases to the atmosphere, such biodegradation is inconsistent with CE principles and therefore does not fall within the proposed definition of recycling.

These proposed definitions are grounded in conventional physical laws (i.e., thermodynamics) and thus universally applicable across technologies and processes. They also simplify and replace the multiple terms in use today.

The definitions are also regulable in that they can be written into law and the associated outcomes are measurable as the amount of material recycled against the definitions. By extension, the rules can be enforced because outcomes can be measured.

The overall effect is that the definition will help facilitate the recirculation of collected plastics and their chemical constituents along multiple recycling pathways to either displace primary or raw materials or become biological nutrients.

7.1 Considerations for Determination of What Constitutes Recycled

When regulating and establishing enforcement protocols, the point at which plastics are deemed to be recycled is critical in order to achieve the purpose of the definition of recycling proposed above.

As uncovered in the jurisdictional scan and through the survey responses, regulators and market actors within the plastics value chain demark the point at which a material is deemed recycled primarily in three different ways:

1. Whatever is collected, that is, whatever enters a material recycling facility (MRF) is deemed recycled. This approach discounts the losses of materials due to contamination, during sorting, and during downstream processing, and it also ignores what the material actually ends up being used for (i.e., final disposition).
2. Whatever is shipped from the MRF (after sorting, excluding processing losses) to a downstream processor that further processes the material is deemed recycled. This approach discounts the losses of materials due to further processing downstream of the MRF and it also ignores final disposition.
3. Whatever is shipped to a manufacturer of plastic products or packaging directly from the MRF or downstream processor as feedstock for manufacturing plastic products, packaging or for making of plastics. This approach captures the yield of polymers, monomers, or constituent chemical building blocks to displace raw materials.

As shown in Table 4, which characterizes a notional chemical recycling process, prematurely declaring a material recycled discounts subsequent processing losses and thus misrepresents and overstates the actual recycling rate.

Consistent with the definition of plastics recycling established above, a plastic product or package should be deemed recycled when it has been rendered into a plastics manufacturing feedstock. Referring to the example in Table 4, this represents a 40% recycling yield as a chemical carrier of the total amount of plastic waste generated with all system losses accounted for.

Table 4: Yield at Various Stages in the Collection, Sorting, and Processing of Plastics in a Notional Chemical Recycling Process

	Yield (t)	Loss (t)	Deemed "recycling rate"
Plastic generated as waste	100		
1) Collected or in-bound to MRF	70	30	70%
2) Outbound from MRF (sorted, excluding processing losses)	63	7	63%
3) Outbound downstream plastics processor			
Processing losses		8	
Yield for fuel market		15	
Yield chemical carrier to make plastics	40		40%

7.1.1 From a Definition of Recycling to a Plastic Recycling Standard

A recycling standard built upon the proposed definition of recycling will require that the following elements be developed as part of the standard:

- Specifications for reporting the amount of plastic supplied into the market;
- A specification establishing a measurement point where plastics are deemed recycled and are deemed as being consistent with the definition of recycling;
- A specification for calculating the recycling rate as the amount of recycled plastic produced at the measuring point expressed as a percentage of the total amount of plastic supplied into the market;
- Specifications for performing mass balance calculations in chemical recycling pathways where recycled chemical carriers are produced and blended into virgin production supply chains. Such rules are not only critical for verifying the recycling of plastics but also for establishing claims of plastics recycled content made by producers of resins and plastic products; and
- Specifications and standards for verifying the processing of non-fossil, bio-based plastics into biological nutrients.

Development of such elements will require broad industry consultation with producers of products using plastics or plastic packaging, mechanical and chemical recyclers of plastics, and plastic resin producers.

8 Conclusion

Defining recycling is of importance to both public policymakers that are seeking to achieve specific environmental outcomes and to the regulated community that must deliver them. A clear definition of recycling is also of specific importance to the plastics recycling sector as it will determine what choices producers make in packaging design and manufacture, collection and recycling supply chain design, and infrastructure investments towards driving a circular economy for plastics in Canada.

By taking an approach underpinned by CE principles and concepts regarding the recirculation of materials, this study proposes the following working definition of plastics recycling:

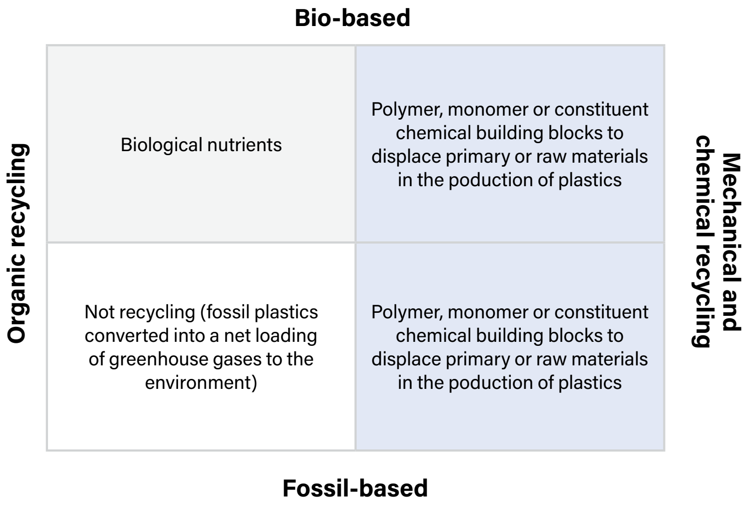
> *Recycling is the reclamation of plastics (as polymer, monomer, or constituent chemical building blocks) in such a manner that they displace the primary or raw materials that are used as chemical building blocks in the production of plastics and plastic products and packaging.*

In the context of non-fossil, bio-based plastics and consistent with CE principles, this definition can be stated as:

> *Organic recycling is the processing of bio-based plastics into biological nutrients.*

Under circular economy principles, only organic recycling of bio-based plastics is recognized as recycling. The definition of recycling in the context of its production pathways is summarized in Figure 4.

Figure 4: Production and recycling of plastics



These definitions are technology blind in that they are applicable across all recycling technologies available today or that may arise in the future.

However, as discussed in the preceding sections, the definition of recycling for fossil-based plastics needs to be applied at the point of the supply chain where it can be verified that the yield of plastics (as polymers, monomers, or constituent chemical building blocks) will displace fossil resources in the production of plastics and plastic products and packaging. This point is typically after the final stage of processing and where the final yield is shipped to manufacturing.

As noted in the Section 5.2 where chemical recycling technologies are applied, only the portion of the chemical carrier outputs that are destined to displace fossil resources in the production of plastics are considered recycled (rather than the portion converted to fuels). To verify this will require instituting mass-balance protocols to identify the balance of materials that were recycled [31].

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Appendix A – Survey Questionnaire

1. How important is the definition of recycling for your business? Under what context (regulated, unregulated) do you currently use definitions to support your recycling / recycling processes? Is a common definition important for purposes of recycling regulations or for making recycling claims to customers?
2. When should something be deemed as recycled? Picked up from the consumer (i.e., collected)? Received at the processor's gate? Shipped from the processor's facility to a downstream processor? Received by an end-market? Used as feedstock in the next cycle of production of products and packaging?
3. What references do you draw your definition of recycling from (technical or academic literature, regulatory definition, industry convention)?
4. The terms closed-loop recycling, open-loop recycling, upcycling and downcycling are used commonly and in some cases interchangeably. How do you interpret these terms?
5. One definition of recycling in use is, "Where materials are collected and processed in such a manner that they can be used in manufacturing to displace demand for the same raw materials produced from virgin sources". How does this definition resonate with you?

Additional Questions for Plastic Collection and Management Businesses

1. What types of plastics do you receive?
2. How do you sort, process, or remanufacture the plastics?
3. What are the outputs from your facility?
4. What end markets are the outputs used for? Do they go for further processing before being reused in manufacturing?

Appendix B – Key Considerations Associated with Plastic Recycling Methods

B.1 Mechanical Recycling

Most mechanical recycling of plastics is conducted by 11 facilities nationwide [2], [72], [73]. Mechanical recycling faces several challenges, often resulting in a final product that is of lower quality than the virgin plastic the product or package was made from.

One challenge associated with mechanical recycling is polymer degradation, which can occur as the polymers are exposed to heat, oxygen, light, and moisture. To combat this degradation, chemical stabilizers have been proposed being used in combination with a "smart control" set-up, where polymer chain repair agents and stabilizers are added that can counteract degradation and improve the recycling rate.

Another challenge arises from recycling a mixed plastic feedstock whereby different plastics have different melting points with the highest used to melt the mixture. This leads to excess energy use and, again, partial degradation of the lower-melting point plastics. Mixed feedstocks also produce lower-quality polymer blends, though it is proposed that the quality of these blends can be improved by adding a chemical "compatibilizer" [27], [74].

To improve the mechanical recyclability of plastics, Environment and Climate Change Canada make several recommendations: that the original manufacturer design for recyclability, that the market for post-consumer resins expands (via mandatory recycled content, for example), that collection and separation systems are improved, and that municipalities and recyclers adopt contracts to ensure constant feedstock supplies [2].

Mechanical recycling typically uses the lowest amount of energy per unit of recycled material produced.

B.2 Chemical Recycling

Chemical recycling techniques can be broadly separated into three categories: solvent purification, decomposition (chemical depolymerization), and conversion (thermal depolymerization). Solvent purification is like mechanical recycling in that the polymers making up the plastic feedstock remain in their original state [30]. The depolymerization techniques, however, aim to break down the polymers within the plastic feedstock into shorter "monomers" (single unit) or "oligomers" (several monomer units), before restoring them back into their polymer chains.

B.2.1 Solvent Purification

During solvent purification, shredded plastic is submerged within a solvent in which the plastic dissolves, but contaminants do not. The solid contaminants can be easily separated out and the dissolved plastic polymers are turned back into their solid form ("precipitated") via the addition of a non-solvent.

Solvent purification can be used with a variety of polymer inputs, including polystyrene (PS), polyethylene terephthalate (PET), polyethylene (PE), polyamide (PA), and polypropylene (PP), given that the feedstock is homogenous and that there exists a solvent that it will dissolve into. For the case of heterogeneous inputs, the mixed feedstock would have to be fed through a series of solvents to extract each polymer type, though this technology is still at the development stage. A concern with this technique is that contaminants may dissolve along the chain of solvents, requiring several solvent and precipitation steps to remove them. In this case, it is very important to understand the expected quantity and cost of each solvent. Even after purification, some impurities are likely to exist within the new polymer chains, making them less durable than virgin polymers. The most energy-intensive steps during solvent purification are the post-purification and drying steps [27], [75].

There are currently no commercial-scale solvent purification companies, though there are a few with pilot-scale testing [75]. One Montreal-based company, Polystyvert, claims to have improved the solvent purification process for recycling of PS plastics. The plastic feedstock is dissolved in a solvent, "purified", and then separated out of the solvent through a novel (and confidential) technology. The used solvent is regenerated for reuse and the recycled PS is pelletized for use in new plastics, with the company claiming that the recycled PS has the same quality as virgin PS and does not undergo any degradation. The company notes that the incoming plastic feedstock can be heterogeneous, but that only the PS will be dissolved and separated for recycling. Polystyvert also states that its process offers low operating temperatures but requires costly filters that must be replaced often. It is unclear what happens to the used filters. They provide no information on recycling yield [76].

One report warns that most solvent purification plants require high energy requirements, making it difficult to scale-up existing processes economically. The report suggests that solvent purification plants target waste feedstocks that cannot be mechanically recycled and would otherwise be incinerated [75].

B.2.2 Decomposition (Chemical Depolymerization)

Chemical depolymerization is the most recent chemical recycling technology, requiring a high-energy input often through high-temperature and high- pressure demands. During chemical depolymerization (also called chemolysis or solvolysis), the polymer chains within the plastic feedstock are broken down into their constituent monomers using a chemical bath. The monomers are then separated from any contaminants through distillation, precipitation, or crystallization, leaving only oligomers, or in some cases, pure monomers [27], [75]. This process is best suited for "condensation polymers" (including PET, PU, PA, PLA), which can be broken down directly into their monomer constituents. However, in the case of PET bottles, for example, chemical depolymerization would have difficulty competing with the mechanical recycling of PET bottles collected through bottle-deposit recycling systems which avoids the energy-intensive step of breaking down polymers [75]. It was suggested that for a PET depolymerization facility to be economic, the minimum feedstock input would be 1.5x104 tonnes/year [19], [77].

The monomer output from recycling PET through depolymerization depends on the chemical used for depolymerization:

- Methanolysis (methanol) takes place at moderate temperatures and pressures;
- Hydrolysis (water) takes place at high temperatures and pressures over a long reaction time; and
- Glycolysis (glycol) is the simplest and oldest technology, existing in some commercial plants, and is best suited for high-quality feedstocks and aminolysis (amines) and ammonolysis (ammonia). Solvents and/or catalysts are often required to aid the reaction [19], [75].

Loop Industries in Terrebonne, Quebec, is a chemical depolymerization plant aiming to recycle PET into mono-ethylene glycol (MEG) and dimethyl terephthalate (DMT) monomers to produce PET and polyester fibers. The company claims that only low heat and no pressure are required, and that the product is "infinitely recyclable" with no product degradation [78].

Similarly, Eastman Chemical Co. in Kingsport, Tennessee, aims to open a new methanolysis plant by 2022 to recycle 100,000 metric tons per year of waste PET. The PET is heated and treated with methanol, broken down into monomers (DMT and ethylene glycol [EG]), purified, and finally used to make new plastics [79].

Among existing plants near commercialization, there is often a lack of reporting on recycling yields, and those that do provide these data fail to show exactly how it was calculated. One report estimates that chemical depolymerization plants can achieve a 90% recycling yield when clean, homogenous feedstocks are used [75].

B.2.3 Conversion (Thermal Depolymerization)

During thermal depolymerization, the plastic feedstock is heated to produce liquid "biooil" and/or gaseous "syngas", typically via gasification or pyrolysis.

Gasification occurs at high temperatures (>700 °C) and with limited oxygen content to prevent combustion. Under these conditions, the plastic polymers are broken down into syngas (a mixture of CO_2, CO, H_2, CH_4, and other hydrocarbons), which has the potential to be upgraded into chemical feedstocks or into precursors to produce more plastics. However, to do so would require heavy processing and therefore high-energy requirements.

Pyrolysis, on the other hand, produces both syngas and biooil by heating the plastics to moderate-to-high temperatures (350–900 °C) in the absence of oxygen. In this case, the syngas is typically used internally for energy production, while the biooil product is further upgraded for use as either a liquid fuel or as a plastics precursor [75]. For use as a liquid fuel, the plastic feedstock can be a heterogeneous mix making it an intriguing option compared to mechanical recycling. Pyrolysis does, however, consume more energy than mechanical recycling. Biooil as a fuel can also be used to produce plastics precursors. In this case the hydrocarbons must be "cracked" into monomers via steam cracking. This, however, requires a homogeneous feedstock of waste plastics and much downstream processing, making it an impractical option [27], [75].

Because the syngas by-product can be used internally as an energy source, some companies claim that the pyrolysis process is self-sustaining with some of the feedstock plastics converted to process fuel. This claim has raised concerns by some that more than half of the plastic feedstock carbon may be lost in oil and gas upgrading to fuel [27]. Furthermore, companies claiming that 100% of syngas will be used to produce energy for the plant also then must assume a high yield of gas production. If this is the case, the company is sacrificing the production of biooil, meaning that less fuels and/or recycled plastics are made from waste supplies [80].

There are some existing commercial-scale thermal depolymerization recycling plants, though none have been commercially viable over the long term. To improve economic viability, many companies are employing the use of catalysts and other novel methods of increasing efficiency/decreasing energy consumption [75].

GreenMantra Technologies in Brantford, Ontario, uses thermo-catalytic depolymerization to convert post-consumer plastics (HDPE, LDPE, and PP) into PE and PP polymer additives to be used in roofing, roads, plastic composites, and other applications. The company claims conversion yields of 95% [81].

Alternatively, Pyrowave in Oakville, Ontario, employs a "high-power microwave technology" to pyrolyze PS. In this process, all labels, films, and impurities are first removed from the feedstock. The clean feedstock is then mixed with silica carbide (SiC), a microwave absorber. A mix of electricity and microwaves are used to break down the PS into monomers, which the company claims utilize 15% less energy than comparable processes. The monomers are then purified and sold to manufacturers with a quality claimed to be identical to virgin plastics and with a monomer product yield of 95% [82].

CSA Group Research

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