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Clarifying European terminology in plastics recycling

Kim Ragaert[1], Cloé Ragot[2], Kevin M. Van Geem[3], Sascha Kersten[4], Yoni Shiran[2] and Steven De Meester[1,5]

Abstract

The increasing activities in plastics recycling have led to a sprawl of terminology describing different technologies and technology categorizations. This creates not only linguistic confusion but also makes it difficult for regulators, investors, corporate leaders and other stakeholders to fully understand the relationship between different technologies, potentially leading to suboptimal decisions on policy, investment, or collaboration. To bring clarity to this topic, this manuscript provides an overview of (i) the different circular pathways for plastics, with a focus on recycling, (ii) the most common categorization of recycling technologies, (iii) what is considered 'recycling' by the European Commission and (iv) some alternative terms used in grey and academic literature to describe recycling technologies.

Addresses

[1] Circular Plastics, Department of Circular Chemical Engineering, Faculty of Science and Engineering, Maastricht University, PO Box 616, 6200 MD, Maastricht, the Netherlands

[2] Circular Economy and Materials Platform, Systemiq, 110 High Holborn, London, WC1V 6JS, UK

[3] Laboratory for Chemical Technology (LCT), Department of Materials, Textiles and Chemical Engineering, Faculty of Engineering & Architecture, Ghent University, B-9052 Zwijnaarde, Belgium

[4] Sustainable Process Technology Group, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands

[5] Laboratory for Circular Process Engineering (LCPE), Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Graaf Karel de Goedelaan 5, B-8500 Kortrijk, Belgium

Corresponding author: Ragaert, Kim (k.ragaert@maastrichtuniversity.nl)

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Plastics recycling, Nomenclature, Circular economy, Recovery.

Introduction

Plastics recycling receives a lot of scientific, industrial and legislative attention as it is considered a key element to realizing a circular economy for plastics [1]. In recent literature, mechanical and chemical recycling of plastics has been thoroughly reviewed [2–4]. In addition, a number of papers have started exploring the overall plastic waste management system [5] and plastic (waste) flows have been documented for Europe [6,7], the USA [8,9] and low- and middle-income countries [10].

The dramatic increase in research and development in this area has led to the emergence of an abundance of nomenclature, which has led to a dispersal of terminology in scientific and layman's literature. In many cases, this is simply using variations of the same expression (such as dissolution vs. solvent-based recycling), but contradictions are also commonly found. For example, literature is divided whether solvent-based technologies are considered chemical recycling or mechanical recycling [11–13]. Moreover, in a bid to appear novel or to dissociate from the negative connotation which chemical recycling may have [14–17], new terms like "molecular recycling" or "advanced recycling" are being introduced in reports and press releases [18–20]. Likewise, the term "upcycling" has found its way into many announcements and even scientific papers [21,22]. Such terms sound attractive but have no formalized meaning and — with advancing insights — it is debatable whether they make scientific sense, especially when considering economics or thermodynamics [23,24].

From a systemic point of view, the term "plastic recycling" is commonly understood to cover not only the specific reprocessing which converts plastic waste to new resources but also the more complete chain which starts at end-of-life of a plastic product and includes collection, sorting and reprocessing [25]. However, the European Waste Framework Directive (WFD) [26], a foundational piece of European legislation, defines the above as "waste management" and considers "recycling" to be only the reprocessing step in this value chain.

While many (often hierarchically structured) illustrations of recycling technologies exist [4,5,27,28], none of them provide a complete and concise overview of the different circular pathways for plastics, their output products, as well as the definition of recycling according to European legislation. This creates not only linguistic confusion but also makes it difficult for regulators, investors, corporate leaders and other stakeholders to fully understand the relationship between different technologies, potentially leading to suboptimal decisions on policy, investment or collaboration. Therefore, this manuscript does not aim to introduce any new terminology, but rather to clarify the exact meaning of the complex terminology already used in plastics recycling, with regard to different names used for a single technology, as well as which technologies lead to what outputs and belong to which category of recycling. Additionally, this article will clarify which technologies fall under the definition of recycling under current European legislation.

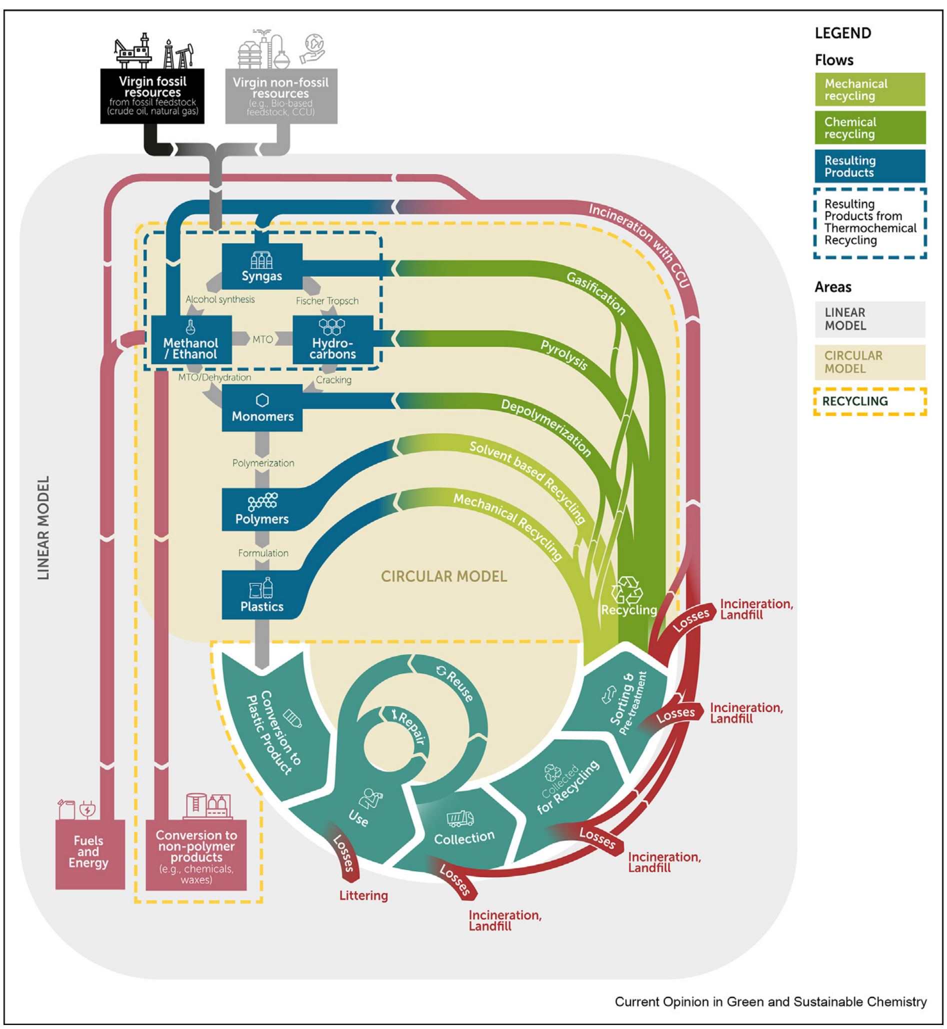
The following aspects are considered out of scope as they have been well reviewed elsewhere: food contact recycling [29], definitions of plastic waste types [30], comparison or ranking of technologies [31–35].

Types of plastic recycling

Figure 1 shows an overview of the different pathways and technologies in the plastic system, by using the most common terminology for distinct recycling technologies. Virgin fossil or non-fossil resources are converted to hydrocarbons, which are consecutively cracked to monomers, which are in turn polymerized into a polymer. By combining different polymer grades and adding in additives or fillers, this process creates plastics, as commonly understood [36]. These plastics are delivered to converters in granulate form, to be turned into plastic products. After their use and potential repair/reuse they become waste and enter the formal collection system, if disposed correctly.

Almost all types of recycling require some level of sorting and washing when entering recycling processes. Although they are not the focus of this manuscript, they have been modelled [32], assessed [33] and reviewed [34] and are clustered under "sorting/pretreatment" in Figure 1.

Figure 1



Overview of the different circular pathways for plastics. Differentiation mechanical/chemical recycling is in accordance with [37] and definition of recycling with [26]. Note how this is not a Sankey diagram and thickness of arrows do not correlate to relative tonnages. Abbreviations used: MTO = Methanol To Olefin and CCU = Carbon Capture and Utilization.

Mechanical recycling — still the most ubiquitous recycling technology [38] — is the shortest loop, extruding the sorted and washed flakes to granulates of recycled plastics, which are often compounded with new additives [39,40], compatibilizers [39,41] or fillers. Depending on the properties of the recyclates, these will be used to create different recycled products [42,43]. The purity of the input material has a significant influence on the properties and quality of the mechanical recycling outputs [44,45].

Solvent-based recycling has two variations. In the first option, the polymer is dissolved and then later precipitated again by either lowering the temperature or adding antisolvent (or both) [27]. As such, it is possible to clean the liquefied polymer from other components (like additives) which made up the plastic [46,47]. The solvent used is specific to the target polymer for dissolution, meaning the technology can also be used as a selective method for recycling parts of a multicomponent product such as multilayers [48]. The second option is a type of non-aqueous washing, typically employing chemicals such as solvents to have an additional effect on the pretreatment, for instance de-inking, de-lamination [48] or increased de-odourization [49,50].

Current European standardization [37] differentiates mechanical and chemical recycling by whether the process is "significantly changing the chemical structure of the material". Mechanical recycling does not (intentionally) change the chemical structure, while chemical recycling does change the structure. Any technology leaving the polymer chain intact is formally considered mechanical recycling. Therefore, solvent-based recycling — if it needs to be categorized — should fall under the definition of mechanical recycling [51,52]. However, there is some confusion surrounding this: (1) the process uses chemicals (the solvents), which frequently leads to the misclassification of this technology as chemical recycling [53,54]. And (2), as mechanical recycling is often commonly linked to the re-extrusion process, the term 'physical recycling' has been introduced to describe both solvent-based and mechanical recycling [51,52] because neither changes the chemical structure of the polymer [35].

All of the techniques described below belong to the chemical recycling category.

Depolymerization reduces the polymer to its consitutive monomers or at least very short segments of polymer chain called oligomers. Methanolysis, hydrolysis, glycolysis and aminolysis are some typical variants of the depolymerization process, their names referring to the specific chemical reactions involved [48,55–57]. Depolymerization typically works well for condensation polymers [5]. However, catalytic cracking is promising for the depolymerisation of polyolefins, with over 85% monomers being reported in certain cases [58].

In pyrolysis, polymers are broken down into hydrocarbons, typically a mix of olefins, aromatics, paraffins and napthenes, with a certain level of gases and char also produced. The ratio between these resulting products is dependent on the input polymer(s), the presence of contaminants, the catalyst (if any), reactor type and process parameters used [59–61]. There is no "typical" pyrolysis process; there are many types of pyrolysis reactors, feeding systems for the reactors and cleaning processes. The resulting product is called a "pyrolysis-oil", which (after purification or refining) can be fed into the cracker to produce new monomers [26].

Gasification uses the highest temperate of all recycling technologies, producing syngas (H_2+CO) and energy in the presence of an oxygen-rich gas [62]. This technology is particularly suited to process a complex mix of waste material and is often used as a waste-to-energy solution for municipal solid waste or biomass waste. From a circularity point of view, chemicals are the desired syngas products (Fischer–Tropsch liquids, ethanol, methanol and so on), which can feed into the system for the production of monomers for further processing [63,64].

After going through any of the above technological pathways, the material ceases to be "waste" [26]. This End-of-Waste point coincides with the transition from green to blue arrows in Figure 1.

Emerging technologies which could be situated between pyrolysis and gasification are known as hydrothermal liquefaction [65,66]. Hydroprocessing technologies (hydrogenolysis [67] and hydrocracking [68]) are a good example, using water as a solvent and operating a high pressure in the presence of hydrogen. However, as they are still in early development, they are not included in Figure 1.

For completeness, incineration is included in Figure 1, but it is not considered recycling (see below). However, if the incineration is paired with CCU (carbon capture and utilization), the resulting CO_2 can be converted to methanol or ethanol and as such re-enter the circular system in Figure 1. Furthermore, some inorganic incineration byproducts (like bottom ash) can be used as fillers in materials like concrete [69]. Regardless of the type of recycling, every step in the life cycle typically has losses either before the recycling process (e.g. littering, rejects) or during the recycling process. Those plastics which are collected but landfilled or incinerated after are considered as losses. Even from those plastics formally collected for recycling, whole truckloads are often rejected at the entry of the recycling plant due to excessive contamination with other materials. These waste plastics are likewise incinerated or landfilled and lost to the circular economy. Considering the losses during the recycling process, it is possible for them to be cascaded to other recycling pathways (e.g. mixed polyolefins from mechanical recycling to pyrolysis). This is marked by the thin green arrows running between recycling technologies in Figure 1.

Table 1 summarizes the technological pathways shown in Figure 1 by recycling category according to European standard [37], as well as listing some commonly used grouping terms or synonyms for these recycling technologies. While these synonyms are not wrong, the authors do suggest only using the terms in the first two columns to prevent confusion.

The term solvolysis deserves some attention. Solvolysis is the chemical breaking of bonds in the presence of a solvent [79], and as such is a synonym for depolymerization. The term is sometimes misused to describe solvent-based recycling [47,52,80]; at times, depolymerization processes have even been described as solvent-based [81].

In addition, a technology-agnostic differentiation is made between closed and open-loop recycling, which refers to how the recycled content is used after reprocessing. In closed-loop recycling, the recycled content is used again for the manufacture of the same type of product as the previous lifecycle (e.g. bottle-to-bottle), while open-loop recycling relates to any other destination for the recycled content (e.g. bottle-to-tray). Open loop recycling is often driven by legislative constraints and is not necessarily of lower value than closed-loop [29].

There are also some terms or even ‘buzzwords’, most often used in layman’s literature, which sometimes cause confusion. In Table 2, the authors have made an effort to clarify the most prominent ones.

Further legal framework and implications

The WFD [26] builds on the definition of “recovery” to define the term “recycling” as “any *recovery* operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations”. Compared to “recovery”, the term “recycling” explicitly excludes the output used for fuels or energy purposes. As such, all technologies demarcated by the yellow dotted line in Figure 1 are considered recycling, while only those also in the yellow field are considered circular pathways.

While the definition of recycling is clear, the thermochemical technologies have raised some new questions regarding the alignment of calculation methodologies for recycling rates, end-of-waste point and recycled content. Mechanical recycling and solvent-based technologies are inherently circular and therefore this recycled content is straightforward to calculate: the amount of input entering the recycling facilities (recycling rate)

Table 1

Summary of categories describing types of recycling according to European standard [30] and their commonly used synonyms in literature [70–78].

Recycling categorization according to European standard [37]	**Technologies**	**Commonly used synonyms**	
Mechanical recycling	Mechanical recycling	Physical recycling	Remelting of plastics [70], conventional recycling [71], thermo-mechanical recycling [72]
	Solvent-based recycling		Dissolution-based recycling [73], dissolution recycling[74], Solvent-based purification[12], solvent purification[17]
Chemical recycling	Depolymerization	Monomer recycling[75], monomer recovery [76], chemolysis [2,77]	
	Pyrolysis	Thermochemical recycling	Thermolysis [78]
	Gasification		No common synonyms

Table 2

Terms commonly used with regard to recycling that have very broad or misleading meanings.

Advanced recycling	A term used by academics or industries when trying to stress the novelty of what they do. As such, the meaning varies with its use. It has been used to describe forms of chemical recycling [60,82,83] or even new methodologies for mechanical recycling [84,85], but has no formal value. Likewise, the term "improved recycling" simply refers to an advancement with regard to current industrial common practice [86,87].
Upcycling	Similar to advanced recycling, upcycling has no formal value and is used in the connotation that waste is "upgraded" to a new resource by a recycling process. In some contexts, it is used to describe recycling of materials to a "higher value" than the original material [88,89], although the sense of that is up for discussion.
Molecular Recycling	A more recent term used to indicate any of the chemical recycling processes [90]; most often, it refers to depolymerization [18–20]. The term is confusing, as the nomenclature supposedly comes from "breaking molecular bonds" and as such would instead refer to recycling beyond the level of the (macro)molecule (to the monomer).
Recovery	ISO 15270:2008 defines it as "processing of plastics waste material for the original purpose or for other purposes, including energy recovery" [37], while the definition by the WFD [26] even explicitly includes processing to fuels. It therefore comprises all possible recycling routes and incineration [91]. However, it is often used contextually as referring only to energy recovery or to the processes counted as thermochemical recycling [92,93] and is then often called "thermal recovery".
Feedstock recycling	Per ISO 15270:2008, feedstock recycling is a synonym for chemical recycling [37]; however, it is more commonly used to describe techniques falling under the thermochemical recycling category [94] (pyrolysis and gasification).

minus the recycling process losses represent the amount of recycled content. However, the output of thermochemical technologies — and even some depolymerization techniques — can produce three final end-uses: (1) end-product that counts as recycling and recycled content (Plastics); (2) end-product that counts as recycling but does not create recycled content (Chemicals & Waxes); (3) end-product that does not count as recycling (Fuels & Energy).

On top of these considerations, petrochemical facilities using thermochemical technologies output as their feedstock represent a large interconnected system where recycled and fossil feedstock cannot be distinguished. It therefore requires a clear calculation methodology, a 'mass-balance approach', to attribute the appropriate quantities of recycled feedstock created, to the end-products defined above [95–97]. The main question is how to attribute it in a representative and credible way to different output, to prevent double counting and incentivize the most circular end-product [98,99]. It is clear that despite these technologies being considered as recycling, the caveat discussed in the WFD notwithstanding, it will not be truly considered as recycling until the EU recognizes a harmonized mass-balance calculation methodology that especially clarifies the use of mass-balance for reporting on recycled content targets.

Finally, and despite the potential contribution to circularity of captured CO_2, incineration with CCU is not counted as recycling, but the development of mass-balance could challenge this for the portion of the output used as products (instead of Fuel & Energy). Yet, incineration brings the embedded energy in the carbon of the polymer chains closest to its thermodynamic dead state, being CO_2 in flue gas, which means that this would be by far the longest loop possible within carbon recycling options.

Conclusions

The field of plastics recycling is in constant development, which gives rise to rich but also confusing terminology on the subject. This manuscript has provided an overview of (i) the different terms used for circular pathways for plastics, with a focus on recycling, (ii) which technology falls under which category of recycling, (iii) what is currently considered 'recycling' by the European Commission and (iv) the most common misleading terms used in layman's and academic literature. To improve clarity, the authors recommend restricting the use of terminology within plastics recycling to those listed in Table 1 and to avoid the confusing terms listed in Table 2.

Credit roles

Kim Ragaert: Conceptualization, Methodology, Writing - original draft, review & editing. Cloe Ragot: Methodology, Writing - original draft, review & editing, Visualization. Kevin Van Geem: Methodology, Writing - review & editing. Sascha Kersten: Methodology, Writing - review & editing. Yoni Shiran: Writing - review & editing, Visualization. Steven De Meester: Methodology, Writing - review & editing.

Editorial disclosure statement

Dr Steven De Meester had no involvement in the peer-review of this article and has no access to information regarding its peer-review.

Full responsibility for the editorial process for this article was delegated to the editor Pieter.

Declaration of competing interest

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Data availability

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