Cascade use indicators for selected biopolymers: Are we aiming for the right solutions in the design for recycling of bio-based polymers?

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Abstract

When surveying the trends and criteria for the design for recycling (DfR) of bio-based polymers, priorities appear to lie in energy recovery at the end of the product life of durable products, such as bio-based thermosets. Non-durable products made of thermoplastic polymers exhibit good properties for material recycling. The latter commonly enjoy growing material recycling quotas in countries that enforce a landfill ban. Quantitative and qualitative indicators are needed for characterizing progress in the development towards more recycling friendly bio-based polymers. This would enable the deficits in recycling bio-based plastics to be tracked and improved. The aim of this paper is to analyse the trends in the DfR of bio-based polymers and the constraints posed by the recycling infrastructure on plastic polymers from a systems perspective. This analysis produces recommendations on how life cycle assessment indicators can be introduced into the dialogue between designers and recyclers in order to promote DfR principles to enhance the cascading use of bio-based polymers within the bioeconomy, and to meet circular economy goals.

Keywords

Design for recyclability, bio-based polymers, system analysis, cascade use

Introduction

Using bioplastics to replace fossil resources and to harness novel polymer properties has received much attention in recent decades. At approximately 7.848 million t a⁻¹ (ca. 0.7%), the global production of bioplastics currently makes up only a fraction of the world’s overall plastic production (European Bioplastics et al., 2015; PlasticsEurope, 2015). While this share is expected to increase significantly in the coming decades, there are major uncertainties with regard to calculating this increase; projections vary between 6% and 30% of the total production volume by 2020 and 2030, respectively (IfBB, 2014; NNFCC and Williams, 2011). Because bioplastics are being introduced gradually to the market, establishing the right infrastructure and proper standards to govern the recycling and treatment at their end of life (EOL) will also become increasingly more relevant. In this regard, successfully implementing optimized recycling cascades for bioplastics is expected to play a key role in decreasing material intensity and increasing material efficiency of limited biomass resources (Carus et al., 2014). The initial experience of recycling plant operators indicates that there are basic needs and problems in treating bio-based polymers. In sorting systems for lightweight packaging, drop-in polymers, such as bio-based polyethylene terephthalate (PET) and polyethylene (PE), are fully compatible with near-infrared (NIR) sorting. In contrast, starch blends and PLA require NIR spectrometers to be more finely calibrated (Hollstein and Wohlebe, 2015). In bio-waste treatment plants, biodegradable and bio-based plastic bags may be increasing the collection quota of organic waste; however, they are not contributing to compost quality. As a result, they are most commonly sorted out and used energetically in thermal treatment plants (Association of German Municipal Utilities, 2013; BGK, 2014).

In order to clarify the situation with regard to EOL paths and options, improvements are needed, starting with the product design. This includes eco-design initiatives and the improvement of product compatibility with different national recycling systems (European Commission, 2015), that is, by formulating advanced criteria for design for recycling (DfR). DfR offers guiding principles for addressing the qualitative requirements of the recycling sector through eco-design. It integrates suitable rules, such as ‘use of recyclable material’, ‘minimizing the number of parts involved in product components’, ‘minimizing the
number of different types of material’, ‘marking parts for easier identification’ or ‘making the product easy to disassemble’ (BIO Intelligence Service, 2011).

The first initiatives and guidelines for DfR were launched at the end of the 1970s. In the last 15 years there have been more specific engineering standards and procedures, such as VDI 2243, the aim of which is to incorporate DfR principles into product design (VDI, 2002). A broad adoption of these criteria is expected to contribute to a better revalorization of polymer waste streams as part of the circular economy strategy, despite other strategies such as the reuse or remanufacturing of products. The impact and benefits of applying DfR principles for better sustainability and performance of polymer products can be evaluated through life cycle assessments. Even though studies on sustainability metrics exist, they only consider cradle-to-gate system boundaries (Tabone et al., 2010) and not extended EOL scenarios.

In order to select life cycle sustainability indicators capable of assessing the influences of DfR on the subsequent cascading use of polymer materials, the authors designed the assessment framework presented in Figure 1. It covers the following qualitative and quantitative aspects of polymer recycling.

- At the product level, the decomposition or recycling of individual bio-based polymer waste flows at their EOL can occur in natural and technical environments. The producers and product designers of bio-based polymer products who use virgin materials can influence these EOL treatment paths by meeting and improving recyclability standards and by applying DfR criteria. The various EOL and recycling paths must first be specified from a system’s perspective in order to specify material flow parameters for comparing intended recovery performance, recovery in the most prevalent final treatment paths and the potentials for increasing material recovery. Therefore, the assessment framework focuses on identifying, characterizing and quantifying the options for enhancing the recyclability of individual bio-based polymer products during the design and manufacturing stages.
- At the circular economy level, quality standards have to be harmonized between key sectors (e.g. composite manufacturing,
packaging and construction industries) in order to guarantee the quality needed when using secondary raw materials derived from bio-based polymers. Thus, these standards can support a more wide-spread use of recycled plastics in polymer processing and thereby help to potentially increase the volume of innovative bio-based plastics that can be recycled through multiple cascade use stages. Therefore, the assessment framework also focuses on identifying relevant polymer innovations and areas where standards can be harmonized. This will enable recycling paths to be identified, which will increase the throughput of secondary raw materials in the future.

- At the recycling sector level, plastic recyclers have to guarantee the quality of recycled polymer materials despite being increasingly faced with challenges posed by novel polymers, additives, etc. This requires ongoing polymer developments and capabilities to be assessed in current and future recycling systems. The extent to which standards for EOL management have to be adapted and harmonized also needs to be identified. Therefore, the framework focuses on identifying and characterizing product standards, recycling processes and quality requirements for secondary raw materials in order to set up qualitative benchmarks for interpreting product-specific recovery rates along the recycling paths.

The aim of this paper is to explore and compile the most crucial aspects (‘trigger points’) of where the design of bio-based polymers conflicts with and where it reinforces circular economy goals for extending further material life cycles of recycled polymers. It also aims to establish a preliminary system of objectives, which would allow quantitative and qualitative criteria to be broken down in order to assess the performance of the cascade use of bio-based plastic waste.

**Materials and methods**

**Scope and limits of this study**

Figure 2 outlines the scope and limits of the study as well as its research design.

Our analysis focuses on three assessment perspectives to qualitatively describe the options for the following: (1) the design of more recyclable friendly products; (2) innovation perspectives for characterizing the effects and optimization potential of recyclability in polymer manufacturing and recycling; and (3) prescriptive goals for recycling bio-based polymer products within technical cycles as part of a circular economy. However, it should be stated that the analysis of the study is limited to the key qualitative aspects of processing, material composition and the recycling of selected bio-based polymers along their product life cycles. In particular, the analysis compares the characteristic differences in the recycling behaviour between innovative polymers and drop-in polymers, thermosets and thermoplastics, and biodegradable and non-biodegradable bioplastics.

In order to adjust the focus for each assessment perspective, we analyse typical recyclability constraints and EOL treatment paths. The focus is primarily on selected polymer recycling routes, which are characterized by the following: a high annual throughput of material flows (such as recycling conventional non-biodegradable (bio-)plastics); the use of common types of additives in the majority of consumer products (such as plasticizers and flame retardants); and the recyclability properties typically important for drop-in polymers with high annual consumption rates (such as bio-PET, bio-PE and bio-PP). The integration of these assessment perspectives and the focus of the qualitative analysis on the life cycle of bio-based polymer materials is also outlined in Figure 2.
In order to organize the qualitative analysis more effectively, the three perspectives and their related research questions were placed into four focus areas (Table 1). This was done to help identify the trigger points at the intersection between polymer design, innovations in polymer recipes, the recycling system and the multi-sectorial circular economy system. Moreover, they were used to characterize the trigger points using criteria for material composition, resource-efficient manufacturing and recyclability criteria consistent with varying recycling systems.

The following tasks and sub-tasks were conducted in order to answer the research questions formulated in Table 1.

**Task 1: Analysis of design options and obstacles for design for recycling.** The most common augmentation steps for enhancing the properties of polymer products were analysed by reviewing the literature. This enabled the main recycling pathways for bio-based polymers and the side-effects of product design on the recyclability of polymers to be identified. Firstly, we analysed polymer design studies with regard to their goals, criteria and principles for designing recyclable polymer products, and selected a sample of plastic products in order to characterize the constraints for improving the recyclability of polymer products. Next, we identified which additives were required for improving the durability and other characteristics of the polymers. Finally, we analysed the unintended effects of polymer properties in the product’s first product life in terms of their impact on recycling efficiency and their consistency with natural and technical cycles in the EOL treatment stages.

**Task 2: Analysis of innovations in manufacturing, recycling and end-of-life treatment.** Qualitative trend analysis explores the possible future trends in polymer manufacturing and recycling, and the potential outcome these may have on achieving recyclability goals. In order to identify the future options and barriers for improving the recyclability of polymer products for increasing recovery rates and resource efficiency of a circular economy system.

**Task 3: Characterization of sustainability goals for a circular economy.** The intention is to create a system of objectives in order to set up a consistent classification system for the performance of cascade use systems. This system of objectives will be used to benchmark the best practices available in polymer cascading.

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**Table 1. Focus areas and research questions for conducting the qualitative assessment.**

| Perspective               | Focus areas                          | Research questions                                                                                     |
|--------------------------|--------------------------------------|--------------------------------------------------------------------------------------------------------|
| Design                   | Enhancing compatibility              | • What are the intended benefits in using additives in polymer design?                                   |
|                          |                                      | • What are the aspects where novel bio-based polymers differ in their properties and in additive applications? |
|                          |                                      | • Which properties of bio-based polymers are similar, equal or comparable to fossil-based references?     |
|                          |                                      | • To which extent are the similarities and differences in product properties, additive application and blending options for conventional and novel polymers offering options for mitigating common conflicts in design for recyclability in the future? |
|                          | Minimization of unintentional effects | • What are the specific contents of e.g. additives, impurities and contaminants in novel bio-based polymers? |
|                          |                                      | • What unintentional side-effects could be created when these novel polymers become part of conventional recycling systems after a first product use phase? |
|                          |                                      | • What are the options for creating fewer unintended side-effects by introducing more harmonized standards, innovative recycling processes and innovative additives? |
| Innovation               | Enhancing manufacturing technologies for closed loops systems \(\text{a}\) | • How could emerging manufacturing trends of polymer products compromise circular economy goals?            |
|                          |                                      | • How can they contribute to enhancing the recyclability of polymer products for increasing recovery rates and resource efficiency of a circular economy system? |
| Circular economy         | Improvements for the circular economy | • How could emerging manufacturing trends of polymer products compromise circular economy goals?            |
|                          |                                      | • Which recycling routes are ‘future-proof’?                                                           |
|                          |                                      | • Which have to be modified gradually to increase the amounts of bio-based polymer waste flows?          |
|                          |                                      | • Which recycling routes will require process innovations?                                              |
|                          |                                      | • How will these adaptations contribute to enhancing the overall cascade use performance of bio-based polymer products? |

\(\text{a}\)With regard to manufacturing processes only.
The first step in assessing the cascade use of biopolymers was to define a system of objectives in Task 3.a in order to identify appropriate assessment metrics for benchmarking the performance of different polymers. In Task 3.b the qualitative and quantitative assessment metrics were allocated along the different life cycle stages, and in Task 3.c a qualitative classification with related quantitative metrics was applied to selected polymer types.

**Task 4: Summary: Are we aiming for the right solutions in design for recycling?** This synthesis aims to draw conclusions from an integrated systems perspective relying on the qualitative characterization of crucial elements for enhanced recycling of bio-based polymer products. These elements were identified at the intersection between design, innovation and standardization, and sustainable use of polymers within a circular economy.

Task 4.a summarizes the findings for the trigger points most important for DfR. In Task 4.b the findings for trend analyses are summarized and conclusions are drawn with regard to the need for harmonized standardization. The gaps in current information and the future-oriented scope for adjusting the monitoring of cascade use are summarized in Task 4.c.

**Results and discussion**

**Analysis of design options and obstacles for DfR**

The environmental strategies of product design are mainly concerned with extending the useful life of the product and with the type of recovery after their EOL.

To provide insights on selected DfR criteria as compiled, for example, by Dwek and Zwolinski (2015), the following common design conflicts can occur when designing polymer products:

- the design of reinforced composites can conflict with the DfR criterion ‘increasing ease of disassembly’;
- the use of fillers and the blending of polymers can conflict with the DfR criterion ‘reducing material variety’;
- the use of flame retardants and plasticizers can conflict with the DfR criterion ‘reducing hazardous material’;
- improper disposal routes can conflict with the DfR criterion ‘increasing recyclability’.

In addition, future trends and drivers for the following design strategies have been identified that extend useful product life (Giudice et al., 2006):

- prototyping for three-dimensional (3D) printing can enhance the DfR criterion ‘designing multifunctional materials’.

One important step in the design process is to choose suitable materials for creating the envisioned affordances, such as affording recyclability (Maier and Jonathan, 2007). Selecting the material used for a certain product purpose determines whether further augmentation steps are needed to meet the design requirements, such as the need for additives in polymer processing and the stabilization of product properties (Giudice et al., 2006). In this sense, the additives are especially important for facilitating polymerization, processing, stability against degradation and improving mechanical, structural and surface properties (Bart, 2006).

Table 2 presents the main fields of application for a selection of the most frequently used additives, as well as the potential negative side-effects.

Achieving DfR criteria is often compromised by design conflicts caused by the intended and unintended side-effects of additives. Unintended side-effects caused by additives include human and eco-toxicity effects, especially through materials that come into contact with food, altered biodegradability and deterioration in further extrusion processes, to name a few of the most important concerns (Bart, 2006; EC Health and Consumers Directorate-General, 2014).

The recycling codes and the food safety symbol currently offer a reliable system for sorting out the additives’ ingredients and the types of polymers found in post-consumer recycling waste. However, they cannot compensate for the lack of a prioritization strategy for appropriate recycling sequences under the conditions of additive restrictions. The most critical additives and their required removal during the respective recycling phase are covered by the Packaging Waste Directive, food contact legislation, the Waste Electrical and Electronic Equipment Directive (WEEE), etc. (Villanueva and Eder, 2014).

Moreover, the choice of material and its compatibility with existing polymer types predetermines the specific EOL treatment of bio-based polymers and how they interact with the other polymers in cascade use with regard to blendability, separability and applicable recycling processes (as shown in Table 3).

As a drop-in solution, the virgin material of bio-based PET can be processed just like its fossil-based competitors in the first product use phase. For recycled PET (both fossil and bio-based), the content of recycled secondary raw materials in the second product use phase is limited by the proportion and molecular weight of the virgin material and by its contribution to the deterioration of the mechanical properties. A content of 30% recycled PET appears to be possible without significantly affecting mechanical properties (La Mantia, 2002).

However, the material recycling of polyolefin and PET waste flows remains low compared to energetic recycling. A major portion of PE (67%) and PET (50%) is energetically recycled in MSW incineration plants and a further 15% is used energetically as solid recovered fuels (SRF) in the cement industry and SRF-based power plants (Wagner et al., 2012). The miscibility of polyactic acid (PLA) with polyolefin and PET for blending is limited, whereas poly (methyl methacrylate) blends allow for a miscibility of up to 50% PLA content (Imre and Pukánszky, 2013).
Table 2. Application of standard additives for selected bio-based polymers (adapted from Bart, 2006; bioplastics magazine, 2015; EC Health and Consumers Directorate-General, 2014; Imre and Pukánszky, 2013; Villanueva and Eder, 2014; Weil and Levchik, 2016).

| Polymer                        | Additives                          | Exemplary types of additives                                         | Product application                        | Possible negative effects on second use phase | Legislative coverage                        |
|-------------------------------|-----------------------------------|-----------------------------------------------------------------------|--------------------------------------------|---------------------------------------------|---------------------------------------------|
| Bio-based PU and PP           | Flame retardants                  | Metal hydroxides, brominated or phosphorus additives                 | Wires, cables, insulation panels and furniture | Can compromise food safety in the 2nd product life | Brominated flame retardants should be removed according to WEEE (2012/19/EU) and RoHS |
| Bio-based PET and PE          | UV-protection, stabilizers and absorbers | Organic and organo-metallic stabilizers                             | Plastic bottles, outdoor equipment         | Maximum sum content of heavy metals 0.001% w/w according to packaging waste directive | Phthalates are regulated under REACH, food contact legislation, and RoHS |
| Bio-based PET and PE          | Plasticizers/softening agents     | Phthalates, citrate esters                                          | Plastic bottles                            | Can compromise e.g., recycling of PET in textile industries |                                                                                            |
| Unsaturated polyester resins and acrylic resins, PE-PLA blends | Fillers and modifiers             | Mineral fillers, such as calcium carbonate                          | Thermally conductive plastics, such as marbles and panels | Can be beneficial for stabilizing recyclate |                                                                                            |
|                               | Compatibilizers                   | Co-polymers, maleic anhydrid                                         | Mixed polymer recyclate                     | Blends in the 1st use phase affect blendability in 2nd use phase |                                                                                            |

PU: polyurethane; PP: polypropylene; PET: polyethylene terephthalate; PE: polyethylene; PLA: polylactic acid; UV: ultraviolet WEEE: Waste Electrical and Electronic Equipment Directive; RoHS: restriction of hazardous substances directive; REACH: European regulation on registration, evaluation, authorisation and restriction of chemicals.

Analysis of trends and innovations in manufacturing, recycling and end-of-life treatment

Emerging trends in recycling, material science and manufacturing are surveyed and analysed qualitatively in the following analytical section. The analysis provides insights into the links between these emerging trends and their resulting options and risks for meeting specific DfR criteria in future product design processes.

The analysis focuses in particular on the following four trends, which were considered because of their wide-spread influence on the options for material recovery alongside the life cycle stages of bio-based polymers:

i. introduction of novel bio-based polymers to broaden design options and recycling paths;
ii. diffusion of novel manufacturing technologies to influence polymer flows and recycling paths;
iii. introduction of novel additives that comply with more restrictive legal thresholds in recycling;
iv. harmonizing standards to improve biodegradability or overall recyclability.

Do emerging materials meet the DfR criterion ‘increasing recyclability’? PLA is an ideal prototype of bio-based polymers as it is polymerized from a biogenic compound (lactic acid), is a mouldable thermoplastic, deteriorates only moderately through a subsequent series of extrusion cycles, can potentially be biodegradable even in home composting, can be blended with PE and PET and can also be a basis for the production of expanded foams (Detzel et al., 2013; Madival et al., 2009). As of today, however, estimated decomposition times of 0.5–1 year in mechanical biological treatment (MBT) facilities and home composting respectively remains questionable (Association of German Municipal Utilities, 2013) and mainly non-durable products are made out of PLA.

Therefore, the future development of novel material recipes and foaming additives for PLA may play an important role if durable, biodegradable, bio-based foams are developed and upscaled. Currently there are several research and development (R&D) activities and medium-scale industrial production capacities that are researching options for manufacturing novel products based on durable poly(d-lactic) acid (PDLA) (Synbra, 2015). The possible applications for expanded PDLA range from food packaging applications to insulation materials with a high potential of substituting conventional expanded polystyrene (Dean, 2013; Synbra, 2015). Furthermore, the developments of PLA-based blends and the testing of suitable compatibilizers may open up further routes for the production of polymer products with enhanced durability and varying recycling routes, such as the pyrolysis of PLA-poly(methylmethacrylat) (PMMA) blends (Groot and Borén, 2010; Imre and Pukánszky, 2013; Lopez et al., 2010).

In summary, the trend analysis shows that (a) manufacturing technologies are a key factor in achieving product performance for durable products made from bioplastics, for example, in
Do manufacturing trends, such as supercomputing, digital prototyping and biomimicry meet the DfR criteria ‘multifunctional materials and reducing material variety’? In the coming decades, the options for programming surface and structural functionality of plastic polymers will offer a whole new range of opportunities for product designers, especially in the manufacturing of nanostructures and nanomaterials (AM Platform and Feenstra, 2014). This implies a variety of chances and risks for the recycling system introduced by novel materials, as well as by new consumer-centric and bio-inspired designs. The emerging options offered by novel moulding technologies, data processing and bio-inspired designs provide an entirely new range of options for product designers when programming material functionality. The manufacturing of ‘lightweight designs’ that mimic natural lattice structures may promote the reduction of energy and material consumption to a significant extent, while simultaneously reducing the variety of materials (Gebler et al., 2014; Sendel et al., 2015; Van Daal, 2015).

In summary, digital prototyping to mimic natural lattice structures will be more widely adopted and is a promising way to reduce material variety and manufacture multi-functional materials in the future.

Do trends such as degradability additives and in-situ biodegradability contribute to meeting the DfR criteria ‘reducing hazardous material and increasing recyclability’? The debates on degradability additives (e.g. for previously non-degradable polyolefins) show that proper EOL management cannot be tackled alone through actions such as changing polymer recipes (Selke et al., 2015). In fact, new standards for biodegradation in
landfills, bodies of water and marine environments will also spread into business practices and may improve the overall metabolic consistency of bioplastics (Mortier, 2014; Vincotte, 2015).

It can therefore be maintained that by-pass solutions for non-biodegradable plastics neither support the path change away from landfill-oriented waste management nor do they contribute to improving the overall recovery rates and recyclability of polymer waste. Furthermore, the analysis suggests that the standardization of bio-based polymers cannot be static. Instead, it has to be embedded into a system of learning between designers and recyclers and has to be more closely oriented to the needs and process conditions of recycling plant operators. If this is not facilitated, the material recovery rates in material recycling will not increase; instead, the energetic recycling of bio-based polymers will be the more dominant EOL treatment path.

**Characterizing sustainability goals for a circular economy**

A classification system for assessing the recyclability performance of bio-based polymers was derived from analysing the most prevalent recycling paths and the qualitative constraints for recyclability.

The qualitative classification system serves as a way to aggregate the assessment metrics along cascading chains for bio-based and fossil-based polymer products.

A key factor in characterizing the recyclability of specific polymer products is the concept of metabolic consistency (Huber, 2000, 2003). It determines the best path for polymer materials in terms of natural material cycles and recycling paths of a circular economy during post-consumer recycling.

Furthermore, the system boundaries for business-as-usual recycling chains and best practice recycling paths are set according to the definition of the material flow system; in other words, whether it can be regarded as a single-stage or multi-stage cascade (Essel et al., 2014).

Several qualitative and quantitative aspects (as suggested by Sirkin and ten Houten, 1994), such as the material’s inherent and intrinsic properties, its energy content and its purity, have to be taken into account when defining and aggregating the cascade use indicators. The conceptualized system of objectives (as depicted in Figure 3), derived from the proposed analysis, enables us to classify the material flows from industrial by-products and post-consumer recycling in terms of the treatment routes they take when returning to the production chains of new goods and services in the industrial and energy sectors. Moreover, it allows us to derive suitable indicators for monitoring the consistency of polymer waste flows within technical or natural environments.

The main material flows are currently induced through bio-based PET and bio-based PE (European Bioplastics et al., 2015), which can be considered a technical nutrient and can be recycled in a multi-stage cascade depending on the product applications and the thresholds for extrusion cycles. This system is well described and often used for quantitative assessment studies and for the qualitative assessment of system design opportunities.

In order to aggregate the proposed indicators, the calculation has to be performed throughout a series of material life cycles for the selected polymer products, as presented in Figure 4.

The accounting procedure includes the following quantitative indicators for cumulating the performance along the paths for energy recovery and material recovery:

- the cumulated energy demand \(\text{CED}_{\text{polymer,recov}}\) (in kWh kg\(^{-1}\)) of recycled polymer required for each waste treatment and material recovery stage;
- the efficiency of material use \(\Delta_{\text{mat, use}}\) (in kg kg\(^{-1}\)) in kg of product recovered per kg of raw material input for individual material life cycles and cumulated along a series of life cycles;
- the substitution factor of virgin materials \(f_{\text{subst}}\) (in kg kg\(^{-1}\)) for each stage where secondary raw materials are recovered in kg of virgin material substituted per kg of input of secondary raw material;
- the energy yields \(\gamma_{\text{energy, recycle}}\) (in kWh kg\(^{-1}\)) for each fraction obtained at EOL through energetic recycling;
- the net calorific value (in kWh kg\(^{-1}\)) and the non-substitutable fractions (in kg kg\(^{-1}\)) of the fossil-based additives that have to be subtracted.

The second indicator category has to account for qualitative criteria, which allows us to explore the potentials for future increases in energy recovery yields and recycle recovery. It also has to take into account future improvements in the quality of secondary raw materials that have fewer impurities and a lower deterioration of the polymer’s rheological properties.

Once these aspects are identified and/or defined, the resulting classification system can rank, for example, the cost of energy and resource demands in the production and recycling phases, the effects of product utility in the use phases produced, which EOL scenario is the most common and which reference products are consistently comparable in this matrix. An overview is presented in Table 4.

In order to achieve a highly resource-efficient recycling of polymers throughout the technical cycles of the circular economy, it is necessary to obtain (a) the highest possible quality and yields in material recovery, (b) the highest possible substitution of virgin materials along a series of material life cycles and (c) the highest possible yields in energy recovery. In this regard, the proposed set of six indicators for quantifying the fractions recovered in energetic and material recycling proves to be suitable for aggregating the assessment metrics required for assessing the actual cascade use performance against future development potentials towards more recycling-friendly polymer products. In particular, the indicators also ensure in the assessment of life cycle metrics that recycling routes where energy recovery is obtainable are outranking EOL routes without energy recovery, such as landflling or biodegradation in the environment.
Conclusion

From a methodological point of view, analysing the incorporation of DfR criteria in actual polymer design activities and examining the most common recycling paths of these polymers through a series of cascading stages helps us to establish the qualitative prerequisites and the goal and indicator systems in order to carry out a systems analysis of the techno-environmental performance of recycling strategies for bio-based polymers.

The most extensive demands for research lie in forecasting future production capacities of bio-based polymers and in surveying the trends for introducing durable bio-based polymer products onto the market. A more accurate projection of future use of long-life durable goods is needed in order to estimate the future release of bio-based waste flows from materials stocks, such as buildings, vehicles and other long-life items, back into the recycling system. In addition to bio-based packaging, one major issue is to establish when a critical mass of bio-based post-consumer waste flows is reached so that material recycling will become a real business case and the recycling infrastructure can adapt to high annual mass streams of bio-based plastic waste.

By assessing the existing solutions for DfR of polymer products, the following conclusions and recommendations should be taken into account in order to promote the right design for enhanced cascading use.

**Recommendations from the design perspective**

- **Promoting polymers with the most flexible EOL options and customizing them with the least harmful additives for the use phase and cascade use:** Recognizing that the range of additives is almost more important in determining the product properties and recyclability than the intrinsic properties of the polymers themselves. It appears that only bioplastic polymers with the broadest possible range of EOL options should be promoted in the long-term.

- **Promoting expandable thermoplastics such as expanded PLA for extended cascade use options:** Recycled polymers

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**Figure 3.** Sustainability rules for cascading use of bio-based polymers within a circular economy. EOL: end of life; PET: polyethylene terephthalate; PE: polyethylene; PP: polypropylene; PLA: polylactic acid; PHA: polyhydroxyalkanoate; MFI: melt flow index.
should be used for durable foam-based products, such as bio-based furniture and insulation materials, since they can serve as a platform for prolonging material use without conflicting with the first premise of food safety.

- **Promoting fully certified, biodegradable and bio-based plastics such as polyhydroxyalkanoates and starch-based polymers for applications with low collection rates or low energy recovery rates**: As the future materials of choice for non-durable products with low collection rates, only biodegradable polymers with a full range of biodegradability (compost, soil, water environments) that are harmonized to the process conditions and retention times of technical facilities and to environmental conditions should be introduced in the long-term.

**Recommendations from the perspective of pre-standardization and innovation management**

- **Rethinking the product design of consumer and durable goods under the food safety premises**: Under the first food safety premise, and based on the observation that there will be new durable products made from foambale bio-based polypropylene and PLA foam, food-safe applications should be prioritized for virgin materials in consumer goods that have high collection quotas and good sortability in NIR sorting processes and durable products should be made from recycled materials enjoying a second product life since additives, such as flame retardants, are mandatory and would compromise food safety in the first place.

- **Pre-standardizing novel consumer-centric manufacturing paths and extended polymer resin coding information**: An enhanced coding system explicitly connecting the information chain between future application options and resin codes is required for bio-based polymers and for novel manufacturing processes such as 3D printing. It would be a valuable solution for linking DfR with cascade use while ensuring resource efficiency for filament use in distributed manufacturing.

**Recommendations from a monitoring and circular economy perspective**

- **Establishing statistical databases for the recycling processes of bio-based industries and novel consumer-centric fabrication labs**: In order to monitor polymer cascades, it would be helpful to have a pan-European statistical database for the average number of extrusion cycles and extended lists of qualitative criteria for additive compatibility and
Table 4. Qualitative classification with related quantitative metrics.

| Polymer types                   | Performance in maximizing resource efficiency & minimizing deterioration over multiple use stages | Energy demand in processing and recycling | Compatibility in end-of-life recovery environments | EOL scenarios | Metabolic consistency at most common EOL paths |
|---------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------|-------------------------------------------------|--------------|-----------------------------------------------|
| Bio-PA, expanded PLA            | High benefits & low polymer deterioration at first EOL                                        | Medium energy demand (LCI)               | Easy collection of bulky waste and recycling via extrusion | Metal recycling in technical environment         | Material recycling in technical environment     |
| Bio-PU, bio-phenol resin, PLA-biofoam | High benefits & high polymer deterioration at first EOL                                        | Medium energy demand (LCI)               | Thermal recovery in waste incinerators           | Treatment and inertization in technical environment | Partially recyclable in technical environment   |
| PLA-blends e.g. with PMMA       | High benefits & medium polymer deterioration at first EOL                                      | Medium to high energy demand (LCI)       | Easy collection, but advanced chemical recycling necessary | Separable partly bio-degradable, partly useful in mechanical recycling | Separation and energetic recovery in waste incineration |
| Starch blends                   | Low benefits and high polymer deterioration at first EOL                                       | Low energy demand (LCI)                  | Not given in natural environments, partly given in technical environments | Inertization via incineration and under defined industrial composting conditions |
| PLA foils and bags              | Low benefits and high polymer deterioration at first EOL                                       | Low energy demand (LCI)                  |                                                |                                                |

EOL: end-of-life; LCI: life cycle inventory; Bio-PU: bio-based polyurethane; PLA: polylactic acid; MFA: material flow accounting; PMMA: polymethacrylate.

compatibilizer options. For emerging technologies, such as 3D printers, these statistics should be automatically submitted electronically to central assessment databases.

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