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Strategic selection tool for thermoplastic materials in a renewable circular economy: Identifying future circular polymers

Evelien Maaskant [1], Wouter Post [1], Marieke T. Brouwer, Daan S. van Es, Eggo.U. Thoden van Velzen *

Wageningen Food and Biobased Research, Bornse Weilanden 9, 6708, WG, Wageningen, the Netherlands

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ABSTRACT

To progress towards a renewable circular economy for thermoplastic materials it is imperative to decouple from fossil feedstocks, to maximise looping strategies and to manufacture occasionally littered articles from readily biodegradable materials. This transition is complex due to the combination of stringent technical specifications that are required for ordinary plastic products and the demands that all end-of-life scenarios foist on these products. The presented strategic material selection tool for fast moving consumer goods in a renewable circular economy prioritises their suitability for the expected end-of-life fates and the contrived technical performance. This framework is tested for 17 common consumer articles and 21 biobased plastics. The strategic selection tool shows that consumer articles that are made from foamed and fibrous plastics, such as matrasses and textiles, can potentially be produced from biobased alternatives, such as biobased poly(ethylene terephthalate) (PET), poly (trimethylene terephthalate) (PTT), poly(butylene succinate) (PBS), poly(butylene succinate-*co*-adipate) (PBSA) and poly(butylene adipate-*co*-terephthalate) (PBAT). On the other hand, the tool also reveals that there are currently no adequate alternatives in barrier (food) packages and in elastomeric products such as tyres, soles of footwear and gloves. Biobased PET is a good polymer for beverage bottles provided that the leakage to the natural environment is minimised with an effective collection, reuse and recycling system. Although there are no viable single-biobased-polymeric alternatives for flexible packages to pack for instance dried foods, solutions could be developed in the form of multi-layered films of various biobased and biodegradable materials. But it would also imply that a dedicated new recycling technology needs to be developed for such multilayer films. The presented tool demonstrates that the technology is ready to start the transition towards a renewable circular economy for consumer articles such as matrasses, cushions, beverage bottles. Simultaneously, new biobased polymeric solutions need to be developed for multiple other applications such as tyres, footwear, gloves and flexible barrier packaging.

1. Introduction

In the past decades, the negative environmental impacts of the production, use and inadequate waste management of fossil-based materials have become more profound. Climate change, global pollution with persistent materials and loss of biodiversity are now major topics in both the scientific arena and the public opinion. All three are related to the use of fossil feedstocks. As a result, there is growing consensus among scientists (European Commission Directorate-General for Research Innovation, 2019; EASAC, 2020), institutions (OECD, 2022; European Union, 2018) and incumbents (SYSTEMIQ, 2022) that a transition from a linear to a circular economy needs to be made for materials. The original blue-print for a circular economy of plastics as presented by the Ellen MacArthur Foundation in 2016 (World Economic Forum, 2016) encompassed creating after-markets for plastic waste, stopping leakage of plastic waste into the natural environment and decoupling of fossil-based feedstocks. Nevertheless, the incumbent petrochemical industry is mostly focussing on mechanical recycling strategies and the development of chemical recycling technologies via multiple pathways (Solis and Silveira, 2020), involving pyrolysis (Kusenberg et al., 2022; Kremer et al., 2022), gasification (Lopez et al., 2018), solvolysis (Ügdüler et al., 2020) and CO_2 capture and utilisation (Berkelaar et al., 2022). Therefore decoupling from fossil feedstocks receives much less attention. Multiple

* Corresponding author.
E-mail address: ulphard.thodenvanvelzen@wur.nl (Eggo.U. Thoden van Velzen).

[1] These authors contributed equally.

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Nomenclature

CA	Cellulose acetate
CAP	Cellulose acetate propionate
DRS	Deposit refund system
EOL	End-of-life
EMA	Equilibrium modified atmosphere
EPR	Extended producer responsibility
EVOH	Poly(ethylene-*co*-vinyl alcohol)
FMCG	Fast moving consumer goods
GHG	Greenhouse gas
HDPE	Polyethylene high density
LCA	Life cycle assessment
LDPE	Polyethylene low density
MAP	Modified atmosphere packaging
PA	Polyamide
PBAT	Poly(butylene adipate-*co*-terephthalate)
PBS	Poly(butylene succinate)
PBSA	Poly(butylene succinate-*co*-adipate)
PC	Polycarbonate
PCL	Polycaprolactone
PET	Poly(ethylene terephthalate)
PGA	Poly(glycolic acid)
PHA	Poly(hydroxyalkanoate)
PHB	Poly(hydroxybutyrate)
$PHBH_6$	Poly(3-hydroxybutyrate-*co*-3-hydroxy-hexanoate) with 6 mol% 3HH
$PHBH_{11}$	Poly(3-hydroxybutyrate-*co*-3-hydroxy-hexanoate) with 11 mol% 3HH
$PHBV_2$	Poly(3-hydroxybutyrate-*co*-3-hydroxy-valeriate) with 2 mol% 3 HV
PLA	Poly(lactic acid)
PP	Polypropylene
PTT	Poly(trimethylene terephthalate)
TPS	Thermoplastic starch
TPU	Thermoplastic polyurethane
OTR	Oxygen transmission rate
WVTR	Water vapour transmission rate

scientists have, however, demonstrated that although we can limit the negative environmental impacts of plastics to some extent with recycling processes, we do need biobased/renewable feedstocks to reduce these environmental impacts substantially (Sheldon and Norton, 2020; vom Berg et al., 2022). Within the context of plastic packages, this has been named "intrinsic sustainable", implying that the environmental impacts over the whole life cycle need to be minimal and when littered the material need to be bio-compatible (Netherlands Institute for Sustainable Packaging (KIDV), 2020).

To progress towards a circular economy for materials, it is inevitable that reuse and recycling systems are decoupled from fossil feedstocks and adjusted to biobased feedstocks. Although logical, this transition also increases the list of demands enforced on these feedstocks. As a result of this underlined complexity, the ambitions and visions for circular plastics that have been drawn up in recent years tend to be very general and it therefore remains unclear how this transition could be accomplished in practice (vom Berg et al., 2022; Kawashima et al., 2019; Ghosh and Jones, 2021). To guide this transition, we propose a definition of a biobased circular economy. A true biobased circular economy has to adhere to the following principles; 1) the system exclusively uses renewable feedstocks, 2) materials are kept in loops as much as possible with the least amount of energy and chemicals spent per loop, and 3) biobased consumer goods need to be processable in all potential end-of-life (EOL) routes that are conceivable for their specific use. The latter implies, for instance, in case a plastic object has a chance of being littered, that it needs to biodegrade in the respective environment in order to prevent material accumulation.

To transition towards a biobased circular economy it is essential to have an overview of the available biobased plastics, their technical performance and their suitability for all EOL routes. This will help to identify applications for which biobased plastics are available with sufficient technical performance and EOL options. Applications for which biobased plastics currently offer insufficient technical performance or EOL options can then be selected for further development work. To assist in this strategical exploration, a strategic material selection tool is presented in this work. The presented framework is built on a two-step approach. First, the required functional performance and desired EOL routes are identified for each of the selected products. Second, both the functional properties and the suitability for all relevant EOL routes are determined for 21 of the most prominent biobased polymers that are currently approaching the market or are already available on a commercial scale. By making a cross-section of materials that comply with functional properties and that have suitable EOL options, the biobased plastics are identified that are the most promising for achieving the technical goals of the circular economy. Furthermore, it identifies current gaps in the existing biobased plastics portfolio and thereby focal points for material research and development in the upcoming decades. Ultimately, the presented selection tool enables stakeholders to develop scenarios for the biobased circular economy of materials and to guide research activities, new product development and waste management optimization in the upcoming decades.

The strategic material selection tool is tested on commonly used consumer articles with a short lifespan, the so-called fast moving consumer goods (FMCGs). These FMCGs dominate waste streams and are therefore focal points of attention in the transition towards a circular economy.

2. Literature review

2.1. Biobased materials in the circular economy

Both fossil-based fuel and material usage contribute substantially to greenhouse gas (GHG) emissions (Herzog, 2009). Renewable energy options are currently being implemented on a large scale to reduce these GHG emissions (IEA, 2021; Eurostat, 2022). The transition towards circular biobased materials is more complex than decarbonising the energy system, since an almost infinite amount of product performance requirements needs to be met by the potential alternatives. Furthermore, multiple reuse and recycling systems are currently being established for fossil-based materials to alleviate environmental impacts. Although well-executed reuse and recycling systems can lower the need for fossil resources, this is currently hardly the case. The limited reuse systems that are currently operational with plastic materials rely on fossil-based feedstocks and fossil-based energy sources for transport and cleaning (Tua et al., 2020; Bø et al., 2013). Additionally, the current plastic recycling systems are still highly dependent on fossil feedstocks (Cimpan et al., 2021). Furthermore, the currently operational recycling systems focus on commonly used fossil-based plastics and tend to exclude newly developed plastics such as biobased plastic materials, as these new materials are regarded as potential contaminants. Consequently, these recycling systems effectively consolidate the status quo of fossil-based materials (Bauer et al., 2022; Gerassimidou et al., 2021). This is named the recycling system lock-in (Aminoff and Sundqvist-Andberg, 2021; Zero Waste Europe, 2021). As a consequence of this lock-in, new biobased materials are classified as "non-recyclable" in design-guidelines, which in extended producer responsibility (EPR) systems with eco-modulation results in higher tariffs for these non-fossil-based plastics (Sheldon and Norton, 2020). This contributes to non-competitive cost prices for biobased plastics and impedes the overall development of biobased plastic products with competitive functionalities.

The biobased plastics industry was kickstarted a couple of decades ago by the development of plastics based on natural polymers such as cellulose and starch. These natural polymers typically need chemical or physical modification in order to allow thermoplastic processing into plastic products such as plastic bags and food containers (Müller et al., 2019). Another approach to obtain biobased plastics is by deriving monomers from biomass (e.g. sugar, starch and fatty acids) which can subsequently be synthesized into thermoplastic polymers. These polymers can be divided in (partially) biobased drop-in polymers or polymers having a unique structure. Drop-in polymers are chemically identical to their fossil based counterparts. Examples of (partially) biobased drop-ins are biobased polyethylene (PE), poly(ethylene terephthalate) (PET), poly(trimethylene terephthalate) (PTT) and polyamide (PA). On the other hand, the development of monomers from biomass allows for the design of polymers that have a chemical structure that is not present in the current fossil based plastic landscape. Examples of such polymers are poly(lactic acid) (PLA), poly(butylene succinate) (PBS), and poly(butylene succinate-*co*-adipate) (PBSA) (Nakajima et al., 2017). Polymers that could be produced from biomass but are currently still produced from fossil based feedstock (e.g. poly(butylene adipate-*co*-terephthalate) (PBAT), polycaprolactone (PCL) and poly(glycolic acid) (PGA)) are also of interest for the transition towards a circular plastics economy due to their high biodegradation rates in different natural environments (Acik, 2020; Becker et al., 2015). A final interesting and unique class of biobased and biodegradable plastics are poly(hydroxy alkanoates) (PHAs) that are produced from (waste) biomass via microbial fermentation. The different types of PHA give rise to a wide range of functional properties, but a common denominator of these polymers is their high susceptibility to biodegradation on land and in marine environments (Sabapathy et al., 2020). In recent years, a substantial range of the aforementioned biobased plastics has emerged from academia and innovative semi-industrial enterprises, and overall production levels are expected to increase in the upcoming decade (Narancic et al., 2020; Zhang et al., 2021; Helanto et al., 2019).

Apart from the lower carbon footprint, these new plastics often offer different EOL options compared to the current fossil-based state of the art (Ghosh and Jones, 2021; Sikorska et al., 2021; Silva, 2021; Lamberti et al., 2020). These alternative routes, such as composting, anaerobic digestion and biodegradability in the open environment, typically revolve around the microbial biodegradation of products (Cazaudehore et al., 2022). Although these new EOL routes widen the waste management options and can prevent the accumulation of carbon based materials in the open environment, it is crucial that newly introduced materials are also accommodated in the existing industrial EOL schemes (re-use, mechanical & chemical recycling and incineration) (Fredi and Dorigato, 2021). This requires adaptation and optimization of the existing EOL infrastructure and development of recycling technology that fits with the unique features of biobased plastics (Dedieu et al., 2022; Karayılan et al., 2021). But as long as key decision makers (governments, producers and EPR organisers) are convinced that the negative environmental impacts of fossil-based plastics can be managed sufficiently with recycling and reuse schemes, it will remain unclear what role biobased plastics will play within the circular economy in the upcoming years.

2.2. Strategic development, new product design and material selection tools

Two main types of design methodologies and tools are used to steer design processes of new FMCGs: strategic tools for the long-term development and new product development tools for the day-to-day design of new products. Both types of tools are essential in material transitions.

Strategic tools, such as technology management tools, enable companies to achieve or clarify policy objectives such as lowering carbon foot-prints or decoupling from fossil feedstocks (Brady et al., 1997). These tools help to make plans over longer periods of time and provide high-level, strategic guidance in product development processes. Various forms of these tools have been developed for specific objectives and audiences. Complete portfolios of products are often assessed simultaneously with such a tool. Their strategic nature allows designers to explore novel ideas, materials and technologies for implementation in product designs. Matrix tools and technology roadmaps tools are two well-known examples of technology management tools (Phaal et al., 2006; Kerr et al., 2013). Matrix tools are relatively simple two-dimensional orthogonal structures in which a specific management issue is addressed and the consequences of potential solutions are mapped in various key dimensions. Four archetypes of matrix tools are discerned: matrices, grids, tables and scored profiles. These matrix tools are typically used by consultants and managers to initiate transition and select technologies (Phaal et al., 2006). Technology roadmaps are strategic tools that graphically depict which technologies need to be mastered as a function of time to complete a business objective (product introduction, transition, etc.). These roadmaps are powerful tools for planning a business objective in relation to resources and exterior dynamic influences (Phaal et al., 2004). Roadmaps are also used in complex situations, such as introductions that involve multiple stakeholders or transitions within heavily regulated domains. For instance, the European Union uses a roadmap in the form of a policy framework to strategically implement biobased plastics (European Commission, n.d.).

New product development tools are routinely used by FMCG industries to navigate the complex design process, which involves multiple stakeholders, interests and trade-offs. In essence, two types of tools are used by the designers of FMCGs; generative and evaluative tools (de Koeijer et al., 2017). Generative tools help to develop new FMCG designs and evaluative tools assess whether the newly envisioned FMCG fulfils all requirements. During the design process the FMCG designer has to veer between the various demands that the future FMCG has to fulfil, which relate to costs, technical performance with multiple criteria (for instance, mechanical strength, optical properties or thermal resistance), producibility, marketing demands, logistical constraints, legal obligations and various environmental impacts (Rundh, 2009; Grönman et al., 2013). To support this process, design tools can be used to structure the process and support the decision-making processes. These design processes typically consist of multiple key stages, such as material selection, conceptual design, the design development and validation. At the first three stages of the design process the focus is on generative tools and at the validation stage only evaluative tools are used. Often multiple iterations of these stages are required to deliver successful packaging designs (Zhu et al., 2022). Life cycle assessment (LCA) based evaluative tools are used to approximate the environmental impact of newly designed packages during these design stages. In the early stages of the design process often simplified LCA-based-tools are used, whereas in the validation stage fully-fledged tools are used (Pollini and Rognoli, 2021). Some well-known packaging design tools that incorporate LCA are Piqet (Verghese et al., 2010), COMPASS (Sustainable Packaging Coalition, 2012), EcoDEX (Schenker et al., 2014) and PackageSmart (Earthshift Global, 2023). Another example is EnvPack, a relatively recent tool to assess the environmental impacts of packages in which different impact assessment methods are combined (Ligthart et al., 2019; Ligthart and Ansems, 2019). With the gradual improvement of these LCA-based-tools and LCA methodologies and the regular updates of LCA databases, the quality of the environmental impact assessments in these tools is also improving. Nevertheless, the quality of the predictions made by these LCA-based tools depends on the presence of reliable data on the EOL fates of the studied FMCG (Venkatachalam et al., 2022). Additionally, the environmental impacts associated with littering are currently not calculated in LCA-based tools, although new approaches have been suggested (Woods et al., 2021). Consequently, the impacts associated with littering remain underexposed in these tools, which consequently favours non-biodegradable plastics. During the design process of FMCGs specific tools can be used for the selection of materials. These material selection tools help the designer balance the different material requirements for a specific application against material properties. A well-known material selection tool is the CES Selector of Granta Design (Granta Design Limited, 2017) that is developed based on the work of Ashby (Ashby, 2011). This selection tool ensures that the most suitable materials are identified and selected for a given application and includes an extensive database of commercially available materials. However, at present these tools do not include biobased plastics.

The final outcome of a design process is the consequence of the prioritisation of the demands that have been placed on the new product; which are must-haves and which are nice-to-haves. In recent years, the reduction of environmental impacts is gradually receiving more attention in the design process. Additionally, the EOL-options for FMCG are shifting. More packages are being collected, sorted, recycled and reused. For several well-collected and reused or recycled packages this has reduced the environmental impacts that are measured with evaluative tools. Although this can be considered as a step in the right direction, to achieve more significant reductions in environmental impacts, the FMCG also needs to be produced from biobased resources (vom Berg et al., 2022) and not negatively impact the natural environment when littered.

To favour the development of biobased packages, a new stage-gate design approach has been suggested by Colwill et al. in which the reduction of environmental impacts is given a higher priority (Colwill et al., 2012). Markevičiūte and Varžinskas recently stressed that biobased materials can only successfully be favoured in new product development tools in case the designed FMCGs fit in the existing locally available EOL management infrastructure and simultaneously fulfil all design factors (Markevičiūtė and Varžinskas, 2022).

Although many design tools have thus far been developed, there is currently no strategic tool available to facilitate the design of FMCGs with biobased plastics and to resolve barriers and lock-ins. There is also a lack of new product development tools that focus on the use of biobased materials. Therefore, this work presents a new strategic design tool that focuses on the transition towards biobased materials for FMCGs in 2030 and offers concrete recommendations with regard to materials. FMCGs were deliberately chosen as they are dominant in various waste streams and hence have the highest impact on the transition towards a circular economy. The timeline of this framework is set at 2030 in order to match with the sustainable development goals (SDGs) of the United Nations (United Nations, n.d.). We acknowledge that other perspectives (economic, social) are also relevant for the definition of future scenarios. However, the technical perspective in itself is already sufficiently complex and deserves separate exploration. To achieve this goal, a number of prominent carbon-based FMCGs are selected as case studies. The presented strategic design tool is unique in its kind, as the EOL options of these thermoplastic materials are set as the most important selection criterion.

3. Methods

3.1. General approach

The strategic selection tool can be operated on common spreadsheet programs or data analysis software like Python's pandas. A schematic representation of the strategic selection tool is given in Fig. 1. The selection tool consists of two tracks, one starting from the FMCGs perspective (upper section, represented with purple colours) and one starting from the biobased plastics perspective (lower section, represented with green colours), eventually merging into one decision tree that is executed for all FMCGs. Both tracks feed into the two assessment steps that are executed in the tool. The first step is the selection of which biobased polymer can fulfil the EOL routes required for a specific FMCG

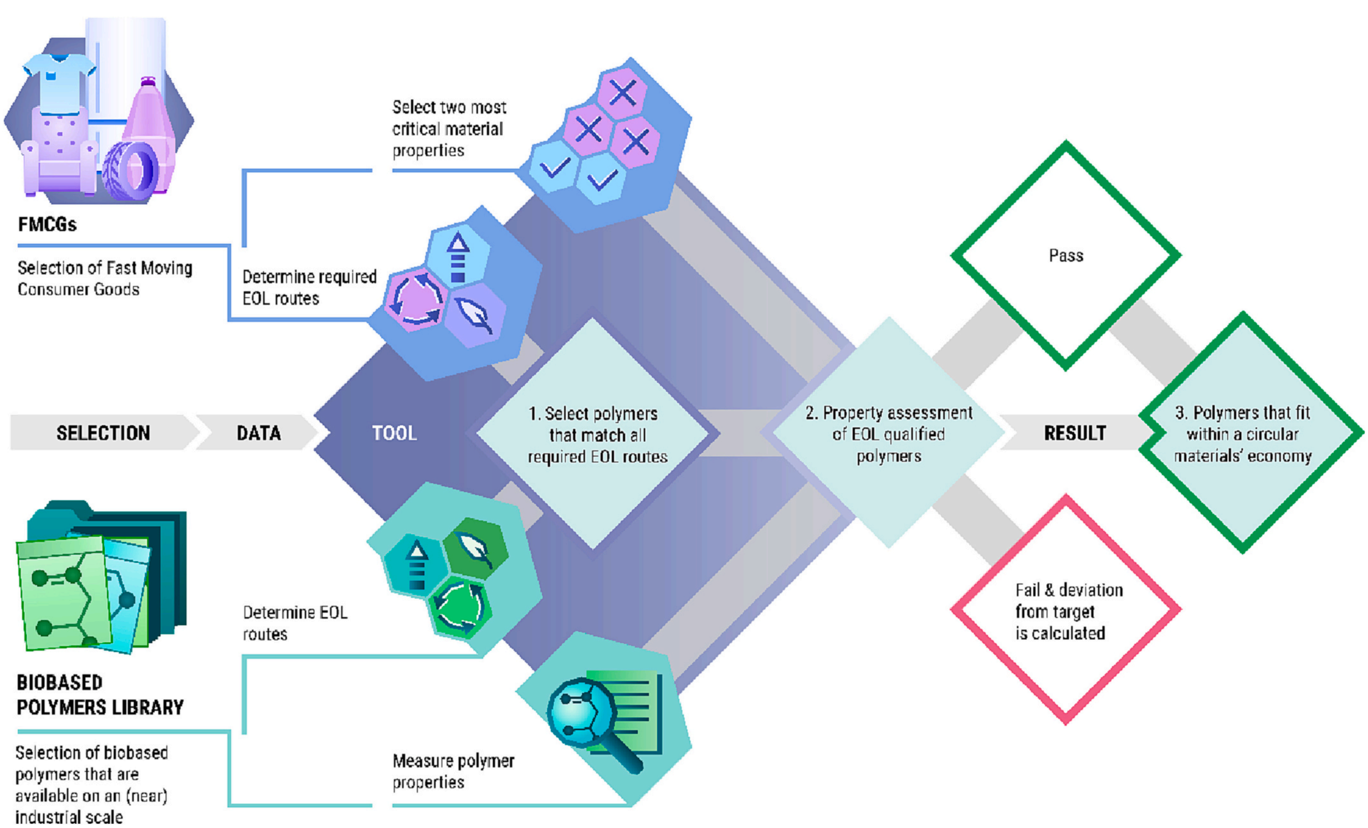

Fig. 1. Schematic representation of the strategic selection tool. EOL: End-of-Life.

group. The second step is the property assessment that determines whether the functionality of the biobased polymers matches the FMCG requirements. This will identify, in step three, which polymers fit within a circular materials economy.

The EOL routes for plastics that fit in the framework of a circular materials economy were selected based on the current academic consensus and boundary conditions described in supplementary information Section S.2.The outcome of this selection process is further described in Section 3.2.

The input of the biobased polymer library track is based on an overview of biobased thermoplastic polymers that are currently available on a commercial scale and are anticipated to be available in sufficiently large amounts in 2030. This overview of (future) commodity biobased polymers and their relevant properties has previously been published (de Beukelaer et al., 2022) and is also shown in Fig. 2. A summary of the relevant material properties is given in supplementary information Section S3. This selection comprises thermoplastic materials that are considered to be a good representation of the current biobased and biodegradable plastic landscape. In this respect, modified natural polymers (cellulose acetate propionate (CAP), cellulose acetate (CA) and thermoplastic starch (TPS)), biobased drop-in polymers (PE, PET, PTT, polycarbonate (PC), thermoplastic urethane (TPU) and PA), biobased polyesters (PLA, PBS and PBSA), and PHAs (poly(hydroxybutyrate) (PHB), poly(3-hydroxybutyrate-*co*-3-hydroxy-valeriate) (PHBV), poly(3-hydroxybutyrate-*co*-3-hydroxy-hexanoate) (PHBH)) that currently available at an industrial scale were selected. These polymers are either fully or partially biobased. In addition, three fossil-based polymers (PBAT, PCL and PGA) were selected for this study as they are anticipated to be made from biobased resources in 2030 and their biodegradation characteristics in different natural environments are considered relevant for the transition towards a renewable circular plastics economy (Nakajima et al., 2017).Additionally, polypropylene (PP) is included, as this fossil-based material is an important reference and biobased PP alternatives are expected to become available in the coming years (Andreeßen and Steinbüchel, 2019). In parallel, it was established with which EOL routes (of which the selection process and definition is featured in Section 3.2) these polymers can be processed effectively. This is described in Section 3.3.

For the input of the FMCG track, 17 products that represent a wide range of the currently relevant FMCGs were selected, and for each chosen FMCG the two most critical material properties per FMCG were defined, see Section 3.4. In parallel, the EOL routes were selected via which the FMCGs need to be managed in a circular economy to prevent undesired environmental impacts such as pollution with persistent materials and uncontrolled CO_2 emission into the atmosphere. These required EOL routes per FMCG are described in Section 3.5.

For each FMCG a separate assessment was made to which extent the selected polymers fit in a circular economy. The most important parameter in this respect is whether a polymer can successfully be managed via all EOL routes that are relevant for this FMCG in a biobased circular economy as defined in Table 3. This 'design for EOL' approach is purposely chosen as it defines the circular feasibility of a polymer and is alternative to traditional engineering solutions that focus on optimizing material and product functionality. Therefore, first a selection of polymers that are compatible with all the required EOL routes per FMCG was made. Second, the compliance of the selected polymers with the two main functionality requirements is assessed for each FMCG. This is done by determining whether the two threshold values are met, and if this is

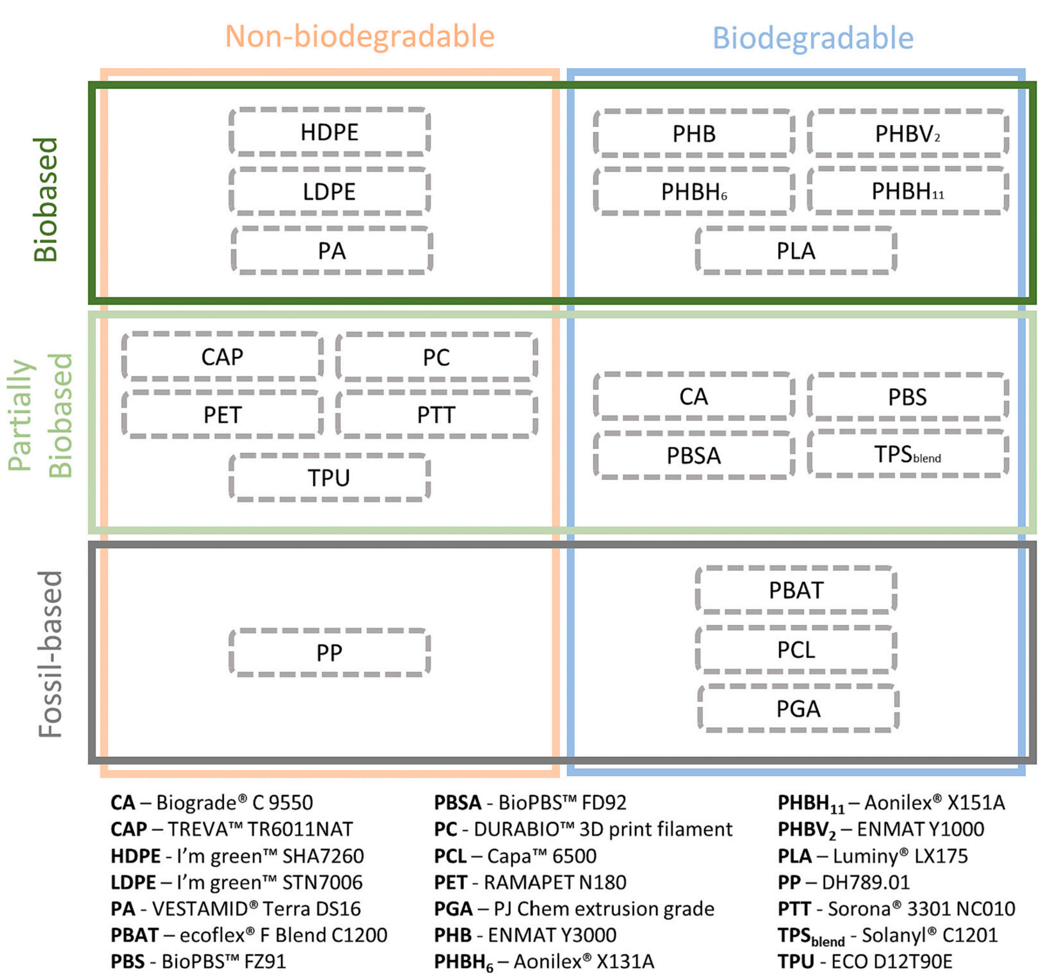

Fig. 2. Categorical overview of the 21 commercially available polymers and their specific grades used as input for the framework presented in this study (de Beukelaer et al., 2022). CA: cellulose acetate, CAP: cellulose acetate propionate, HDPE: high density polyethylene, LDPE: low density polyethylene, PA: polyamide, PBAT: poly (butylene adipate-co-terephthalate), PBS: poly(butylene succinate), PBSA: poly(butylene succinate-co-adipate), PC: polycarbonate, PCL: polycaprolactone, PET: poly(ethylene terephthalate), PGA: poly(glycolic acid), PHB: poly(hydroxybutyrate), $PHBH_6$: poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) with 6 mol% 3-hydroxyhexanoate, $PHBH_{11}$: poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) with 11 mol% 3-hydroxyhexanoate, $PHBV_2$: poly(3-hydroxybutyrate-co-3-hydroxyvaleriate) with 2 mol% 3-hydroxyvaleriate, PLA: poly(lactic acid), PP: polypropylene, PTT: poly(trimethylene terephthalate), TPS: thermoplastic starch and TPU: thermoplastic urethane.

not the case how substantial the mismatch with the desired functionality is. This renders a list of biobased polymers that have the potential to replace the fossil-based plastics that are currently used to produce the respective FMCGs from both and EOL and functionality point of view. This evaluation can subsequently be used to determine whether material modification is expected to yield a better match with functionality requirements or if a material is unsuitable for a certain application in general. Economic, social or environmental considerations were not included in the selection tool. The tool is developed for European FMCGs in 2030 with a lifespan of <5 years and a market size of >1 kton, see supplementary information Section S.1 for a more detailed description of all boundary conditions and presumptions.

3.2. Examined end-of-life routes

Seven EOL routes were selected as the looping strategies and waste management processes that fit in a circular economy framework. These are, in order of decreasing resource efficiency: reuse, mechanical recycling, chemical recycling via de-polymerization, industrial composting, aerobic digestion, biodegradation in nature and incineration. These EOL routes follow the general order as described in the waste hierarchy (European Union, 2008).

- Re-use implies that a product can and will have to be re-used after its first functional cycle without reshaping and/or reprocessing.
- Mechanical recycling implies that the product can and will be sorted and cleaned, and allows for thermoplastic reprocessing into a new product of the same quality that can be used in the same application (Aubin et al., 2022).
- Chemical recycling implies that the product can be efficiently and selectively depolymerized back to its original monomer(s) or its direct precursors which can subsequently be purified and (re)polymerized into new products of the same quality (Payne and Jones, 2021; Thiyagarajan et al., 2022).
- Industrial composting implies that a product can and will biodegrade for at least 90 % of its initial mass upon exposure to a temperature of 58 °C within a period of 6 months following standard EN 14995 (Standards, 2006). Here, biodegradation is defined as the biological conversion of a material by microbes and/or fungi into water, carbon dioxide and residual biomass.
- Anaerobic thermophilic digestion implies that a product can and will biodegrade for at least 50 % upon exposure to a temperature of 52 °C within a period of 2 months following standard EN 14995.
- Incineration implies that a carbon-based material can be converted into mainly carbon dioxide, water and char by heating in the presence of oxygen.
- Biodegradation in nature implies that a product can and will biodegrade for at least 90 % of its initial mass upon immersion in soil at a temperature of 25 °C within a period of 2 years following standard ASTM G160-12(2019) (International, 2019). Biodegradation in soil is selected as a criterium for polymer accumulation in the nature as it is the most quantifiable method available to assess this requirement. Nevertheless, the authors realize that other environments (e.g. fresh water and marine conditions) might be of relevance for certain product groups. Furthermore the 2 year cut-off point of ASTM G160-12(2019) might not reflect the true accumulation potential of certain product-material combinations. New methods and standards to quantify the accumulation potential in more detail are therefore desired, which will subsequently increase the effectiveness of the presented selection tool.

3.3. End-of-life routes for the biobased polymers

The suitability of the selected biobased thermoplastic materials for the seven selected EOL routes is listed in Table 1. All selected biobased polymers were defined to be suitable for reuse, mechanical recycling and incineration, whereas the suitability of the biobased polymers for the other EOL routes varies strongly. Assessing the suitable EOL options for

Table 1
Qualitative assessment of the suitability of end-of-life routes for various biobased thermoplastic polymers, showing the plus symbol (+) when the route is deemed suitable and the minus symbol (−) when it is not. CA: cellulose acetate, CAP: cellulose acetate propionate, HDPE: high density polyethylene, LDPE: low density polyethylene, PA: polyamide, PBAT: poly(butylene adipate-co-terephthalate), PBS: poly(butylene succinate), PBSA: poly(butylene succinate-co-adipate), PC: polycarbonate, PCL: polycaprolactone, PET: poly(ethylene terephthalate), PGA: poly(glycolic acid), PHB: poly(hydroxybutyrate), $PHBH_6$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 6 mol% 3-hydroxy-hexanoate, $PHBH_{11}$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 11 mol% 3-hydroxy-hexanoate, $PHBV_2$: poly(3-hydroxybutyrate-co-3-hydroxy-valeriate) with 2 mol% 3-hydroxy-valeriate, PLA: poly(lactic acid), PP: polypropylene, PTT: poly(trimethylene terephthalate), TPS: thermoplastic starch and TPU: thermoplastic urethane.

Material	Re-use	Mechanical recycling	Chemical recycling	Industrial composting	Anaerobic digestion	Incineration	Biodegradation in soil
CA	+	+	−	+[a]	−	+	−
CAP	+	+	−	−	−	+	−
PA-10,10	+	+	+	−	−	+	−
PBAT	+	+	+	+	−	+	+
PBS	+	+	+	+	−	+	−
PBSA	+	+	+	+	−	+	+
PC	+	+	+	−	−	+	−
PCL	+	+	+	+	−	+	+
HDPE	+	+	−	−	−	+	−
LDPE	+	+	−	−	−	+	−
PET	+	+	+	−	−	+	−
PGA	+	+	+	+	+	+	+
PHB	+	+	+	+	+	+	+
$PHBH_6$	+	+	+	+	+	+	+
$PHBH_{11}$	+	+	+	+	+	+	+
$PHBV_2$	+	+	+	+	+	+	+
PLA	+	+	+	+	+	+	−
PP	+	+	−	−	−	+	−
PTT	+	+	+	−	−	+	−
TPS	+	+	−	+	+	+	−
TPU	+	+	-[b]	−	−	+	−

[a] CA is mostly considered to be non-compostable and non-digestible (Gadaleta et al., 2022), however, in this study a certified industrially compostable CA grade was used.

[b] The exact chemical structure of the used TPU grade is not publicly available, but the material likely consists of polyester and polyether compounds. As polyethers cannot be chemically recycled according to the definition in this work, TPU is scored non-suitable for chemical recycling.

the remaining routes was done by evaluating the chemical structure (in case of chemical recycling: the presence of easily and selectively hydrolysable chemical bonds) or, for the EOL routes that depend on biodegradation (industrial composting, anaerobic digestion, and biodegradation in soil), by consulting the TUV certification (TÜV® Austria, n.d.) for the specific grade of polymer used in this study (de Beukelaer et al., 2022) or by consulting the renewable carbon infographic (nova-Institute (Germany), 2021).

This qualitative assessment clarifies that only a limited number of biobased thermoplastic polymers is suitable for all seven likely EOL routes, and since most applications require the object to be manageable via multiple EOL routes, this effectively limits the amount of candidate polymers that is suited for the assessed application within a circular biobased economy.

3.4. Selection of fast moving consumer goods

Five exemplary product categories were chosen that are currently predominantly produced by fossil-based plastics: barrier plastics, rigid plastics, foamed plastics, fibrous plastics, and elastic products. Within each product category several well-known applications are chosen, these are listed in Table 2. This selection aims to cover some of the most relevant applications, but is inherently arbitrary in nature. Furthermore, this table also shows the two most critical material properties and their threshold for the chosen applications. A more detailed justification of the threshold values is given in the supplementary information Section S4. Although for most applications dozens of (technical) material properties are relevant, we have constrained ourselves to two critical material properties to enable a first approximation of the suitability of biobased materials for the chosen consumer articles.

Table 2
Selection of the five product categories and the 17 fast moving consumer goods products therein, and of each selected product the two most critical material properties. OTR: oxygen transmission rate, WVTR: water vapour transmission rate, MAP: modified atmosphere packaging (as is common for meat, meals, cheese and fish), EMA: equilibrium modified atmosphere packaging (as is common for perishable fruits and vegetables).

Product category	Property 1	Property 2
Barrier plastics	OTR @100 μm, 23 °C (mL/m^2.day.bar)	WVTR @100 μm, 23 °C, 85 % RH (g/m^2.day)
Dry food packaging	≤80 (50 % RH)	≤1
Fresh food packaging (MAP)	≤40 (85 % RH)	≤1
Fresh food packaging (EMA)	≥200 (85 % RH)	≥0.4
Beverage bottles	≤40 (85 % RH)	≤50
Personal care packaging	≤800 (50 % RH)	≤50
Rigid plastics	E-modulus (MPa)	Elongation at break (%)
Home appliances	≥2000	≥10
Toys	≥1000	≥10
Electronics casing	≥2000	≥10
Foamed plastics	E-modulus (MPa)	Melt strength (mN)
Matrasses	≤1500	≥50
Furniture cushioning	≤1000	≥50
Protective packaging[a]	≥2000	≥10
Fibrous plastics	Stress max (MPa)	Glass transition temperature (°C)
Clothing	≥20	≤−20 or ≥70
Carpets & furniture	≥30	≤0 or ≥50
Disposable hygiene products	≥15	≤−20 or ≥50
Elastic products	Stress max (MPa)	Elongation at yield stress (%)[b]
(car/bike) Tyres	≥50	≥20
Footwear	≥10	≥10
(medical) Gloves	≥5	≥100

[a] For example expanded polystyrene (EPS) foam.
[b] When no yield stress is observed, the elongation at break is taken.

3.5. End-of-life routes for the fast moving consumer goods

Besides the most prominent functional requirements of the selected FMCG, also the EOL routes per FMCG were defined. This encompasses both the EOL route(s) which these products currently follow after-use and those they need to follow in order to fit in a circular economy. The same list of seven EOL routes is considered for the polymers as described in Section 3.2 as for the FMCGs.

In order for re-use to be a required EOL route the product should allow for multiple use cycles. This implies that the plastic product needs to be cleaned and decontaminated effectively with each loop. This is feasible for multiple rigid plastics and secondary packaging applications. Primary, reusable plastic packages also need to be reclose-able. For many primary packaging applications, effective decontamination processes have not been developed yet. Furthermore, also reclose-able modified atmosphere packages have not been developed, yet. As a result, most food packaging categories cannot be demanded to be reusable. Mechanical and chemical recycling are considered as the most important looping strategies within the circular economy for plastic packages as they require the least amount of resources (energy, water and chemical use) to close the loop, after re-use. Therefore, all consumer goods covered in this study should allow for at least these two EOL routes. For industrial composting and anaerobic digestion a co-benefit (i.e. contamination with an inseparable fraction of organic material) needs to exist in order to make these routes favourable. Incineration is considered to be the least desirable EOL route included in this study, as it intrinsically results in the highest level of greenhouse gas emissions, therefore it is regarded as a last resort. Nevertheless, in the future, it might be possible to capture (store and use) the carbon dioxide gas emissions after incineration (CCSU). This would enable a new looping strategy towards carbon-based materials which would require ample amounts of renewable energy (Thunman et al., 2019). Finally, biodegradation in the open environment is considered to be crucial for those products that are used in the respective environment, have a high risk of being littered or will emit persistent chemicals or microplastic particles due to leaching or abrasion upon use. Food packaging (barrier plastics) is by far the main component of urban litter (Kedzierski et al., 2020; Ballatore et al., 2022) and should, therefore, be biodegradable in a circular biobased economy. Although fibrous products, such as textiles, as such are less prone to end up in the natural environment, the persistent microplastic fibres resulting from abrasion (e.g. during machine washing) are very likely to end-up in the natural environment, and therefore clothing should be biodegradable. The same is true for rubber tires and to a lesser extent footwear (elastic products), of which abrasion also causes microplastic pollution. The collective overview of the required EOL routes per product category is depicted in Table 3.

4. Results and discussion

The results of the selection tool are listed in Supplementary Information Section S.5. For each product category an overview is given of which biobased polymers are suited or partially suited. First, an overview of all polymers that pass the EOL-scenario test is given for each category. This is a result of combining the input conditions stated in Sections 3.3 and 3.5. Polymers that cannot fulfil all EOL routes required for a specific product category are not listed and subsequently not assessed with respect to functionality. Second, for those polymers listed, the values of the most relevant material properties (Supplementary information Section S3) are given. Furthermore, the tables show the outcome of the threshold value test for these respective properties. Here it is shown whether a polymer meets the required material properties (i.e. pass) or not (i.e. fail). In the latter case, a relative deviation with respect to the target value is given as a percentage. This is insightful, since a small deviation indicates that probably a match between material properties and requirements can be attained by material optimisation (e.g. use of additives, use of a different molecular weight

Table 3
Overview of end-of-life routes (waste management technologies) with which each fast moving consumer good product needs to be processible after-use to fit in a circular economy in 2030. A plus symbol (+) is given when that end-of-life route must be available and a minus symbol (–) when it is not suitable for this product and thus cannot be used. MAP: modified atmosphere packaging (as is common for meat, meals, cheese and fish), EMA: equilibrium modified atmosphere packaging (as is common for perishable fruits and vegetables).

Product category	Re-use	Mechanical recycling	Chemical recycling	Industrial composting	Anaerobic digestion	Incineration	Biodegradation in soil
Barrier plastics							
Dry food packaging	–	+	+	+	+	+	+
Fresh food packaging (MAP)	–	+	+	+	+	+	+
Fresh food packaging (EMA)	–	+	+	+	+	+	+
Beverage bottles	+	+	+	–	–	+	+
Personal care packaging	+	+	+	–	–	+	–
Rigid plastics							
Home appliances	+	+	+	–	–	+	–
Toys	+	+	+	–	–	+	–
Electronics casing	+	+	+	–	–	+	–
Foamed plastics							
Matrasses	+	+	+	–	–	+	–
Furniture cushioning	+	+	+	–	–	+	–
Protective packaging	+	+	+	+	+	+	+
Fibrous plastics							
Clothing	+	+	+	–	–	+	+
Carpets & furniture	+	+	+	–	–	+	–
Disposable hygiene products	–	+	+	+	+	+	–
Elastic products							
(car/bike) Tyres	+	+	+	–	–	+	+
Footwear	+	+	+	–	–	+	+
(Rubber) Gloves	–	+	+	–	–	+	–

distribution, or orientation of the polymer chains) or by lowering the user expectation. To illustrate the functionality of the selection tool, the output for two of the selected FMCG products, dry food packaging and beverage bottles, is shown in Table 4 and Table 5, respectively.

Table 4 lists only five different polymers for the category dry food packaging which implies that according to the selection tool input, only these polymers match all the EOL requirements that were set for dry food packaging (mechanical recycling, chemical recycling, industrial composting, anaerobic digestion, incineration and biodegradation in soil as depicted in Table 3). Furthermore, Table 4 lists the performance of these five polymers with respect to the OTR and WVTR and the required target values as defined in Table 2. These results show that the OTR of almost all polymers (except $PHBH_{11}$) pass the threshold value, but that there is a large functionality mismatch with respect to the WVTR target values that are required for this application. This implies that there is no single biobased material that can replace the current fossil-based benchmarks. This is not surprising as the current state of the art for this application typically consists of multi-layer flexible packaging films that combine polymer films with low OTR (e.g. PET, PA, EVOH) and low WVTR (e.g. PP or PE) values (Baele et al., 2021). The development of biobased multilayer materials that can follow all EOL routes stated in Table 3 is therefore considered a crucial development route for the upcoming decades. Currently, multilayer materials are predominantly incinerated, mechanically recycled into mixed plastics

Table 4
Example of the selection tool output for dry food packaging. OTR: oxygen transmission rate, WVTR: water vapour transmission rate, PHB: poly(hydroxybutyrate), $PHBH_6$: poly(3-hydroxybutyrate-*co*-3-hydroxy-hexanoate) with 6 mol% 3-hydroxy-hexanoate, $PHBH_{11}$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 11 mol% 3-hydroxy-hexanoate, $PHBV_2$: poly(3-hydroxybutyrate-co-3-hydroxy-valeriate) with 2 mol% 3-hydroxy-valeriate.

Polymer	Material properties		Threshold value test: dry food packaging	
	OTR @100 µm, 23 °C, 50 % RH (mL/m^2.day. bar)	WVTR @100 µm, 23 °C, 85 % ΔRH (g/m^2.day)	OTR ≤80 @100 µm, 23 °C, 50 % RH (mL/m^2.day. bar)	WVTR ≤1 @100 µm, 23 °C, 85 % ΔRH (g/m^2.day)
PGA	0.1	2	Pass	Fail (65 %)
PHB	20	6	Pass	Fail (452 %)
$PHBH_6$	63	12	Pass	Fail (1064 %)
$PHBH_{11}$	114	8	Fail (43 %)	Fail (692 %)
$PHBV_2$	21	6	Pass	Fail (453 %)

Table 5
Example of the selection tool output for beverage bottles. OTR: oxygen transmission rate, WVTR: water vapour transmission rate, PBAT: poly(butylene adipate-co-terephthalate), PBSA: poly(butylene succinate-co-adipate), PCL: polycaprolactone, PGA: poly(glycolic acid), PHB: poly(hydroxybutyrate), $PHBH_6$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 6 mol% 3-hydroxy-hexanoate, $PHBH_{11}$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 11 mol% 3-hydroxy-hexanoate, $PHBV_2$: poly(3-hydroxybutyrate-co-3-hydroxy-valeriate) with 2 mol% 3-hydroxy-valeriate.

Polymer	Material properties		Threshold value test: beverage bottles	
	OTR @100 µm, 23 °C, 85 % RH (mL/m^2.day. bar)	WVTR @100 µm, 23 °C, 85 % ΔRH (g/m^2.day)	OTR ≤40 @100 µm, 23 °C, 85 % RH (mL/m^2.day. bar)	WVTR ≤50 @100 µm, 23 °C, 85 % ΔRH (g/m^2.day)
PBAT	516	27	Fail (1191 %)	Pass
PBSA	397	66	Fail (894 %)	Fail (31 %)
PCL	561	7	Fail (1302 %)	Pass
PGA	0.4	2	Pass	Pass
PHB	23	6	Pass	Pass
$PHBH_6$	71	12	Fail (76 %)	Pass
$PHBH_{11}$	127	8	Fail (218 %)	Pass
$PHBV_2$	22	6	Pass	Pass

and chemically recycled by pyrolysis (Kremer et al., 2022), however, when the monomers of the individual layers can be separated, these multilayer materials can fit in a circular economy. Based on the results shown in Table 4, PGA is an interesting candidate to be included in these developments as it is closest to passing both functionality requirements.

Table 5 shows the selection tool output for beverage bottles. For beverage bottles more polymers pass the initial EOL test compared to dry food packaging. This is attributed to the fact that industrial composting and anaerobic digestion are not considered required EOL scenarios for this product category. Another difference compared to the results of dry food packaging is that the requirements for the OTR are more stringent which makes that only three polymers pass the threshold value. The WVTR values on the other hand are much less demanding and therefore PGA, PHB an $PHBV_2$ pass all requirements that were set and are therefore deemed to be interesting starting points for the development of circular beverage bottles. It should be noted that the processability of these three polymer compounds is known to be challenging, but this has not been taken account in this assessment. Alternatively, in countries with effective collection systems such as deposit refund systems, the littering rate of beverage bottles is relatively small (Christin Belke et al., 2020). Under this condition, politicians could decide to exempt beverage bottles from the need to be biodegradable in nature and bio-PET could be used to replenish losses in these recycling systems. As the collection and recycling infrastructure for this product-material combination is already well established in European countries, continuation of this circular system in combination with bio-PET feedstocks is likely to be the politically preferred option. However, in case we would like to address the negative environmental impacts of the limited remaining littering rate, then conversion to biodegradable materials will be imperative.

Upon reviewing the selection tool output of the other products in the category barrier plastics in Supplementary information Section S.5, it becomes clear that for personal care packaging many biobased polymers pass both the EOL and functionality threshold value test. On the other hand, the output for equilibrium modified atmosphere (EMA) packaging shows at first glance that no biobased alternatives are suitable, which is attributed to a too high OTR requirement. In practice this is solved by selective puncturing of the films and this could be done for the biobased alternatives as well, implying that all biobased polymers would qualify. For modified atmosphere packaging (MAP) packaging, similar results and output are obtained as for dry food packaging (Table 4) which implies that multilayer solutions should be investigated for this category too.

The output for products in the rigid plastics category yields much more suitable options than the barrier plastics. This is attributed to the anticipation that less EOL requirements have to be fulfilled in order to reach a circular system. Biobased PET, PTT and PC all pass the *E*-modulus and the elongation at break criteria and are therefore considered to be the most suitable plastics for the production of home appliances and electronics casings. In addition, PA-10,10 and $PHBH_6$ also pass the less stringent criteria set for toys and are within development range for the other two categories. This also applies to PLA, which fails on the elongation at break requirement, for which routes to increase its toughness are well known in academia and industry (Zhao et al., 2020).

The results in the product category foamed plastics show that for matrasses and furniture cushioning 14 materials pass the EOL requirements, but that only PBS and PBSA also qualify when the functionality (i.e. modulus and melt strength) are taken into account. Furthermore PA-10,10 lies well within development range for these two products. Compared to the aforementioned cushioning foams, protective packaging foam has both a different EOL profile and different functionality thresholds. As a result, only five materials are considered from an EOL point of view and none of these materials pass both functionality thresholds. Increasing the stiffness of $PHBH_6$ seems to be the most straightforward development route to obtain a circular system for this specific product category provided that a thermoplastic material is required.

Fibrous plastics are assessed based on their maximum strength and their glass transition temperature (T_g). The selection tool output indicates that PCL, PBAT and PBSA are a good match considering both EOL and functionality for clothing and carpet and furniture textiles, although the latter product category would require a slight boost in strength. Regarding PCL it has to be stressed that the T_g was selected as discriminator in order to safeguard that the fibrous products do not undergo a physical transition during use and/or cleaning. Logically this also applies to the melting temperature (T_m) of a polymer and when this is taken into account, PCL, with a T_m around 50–60 °C, does not qualify for the functionality assessment. PLA, PBS, PET and PC all qualify for use in carpets and furniture textiles, but their insufficient biodegradation characteristics (in soil) prevent them from being taken into account for clothing. PLA also qualifies for use in disposable hygiene products. The on-going development of both PLA (Carbiolice, 2021) and PBS (Liu et al., 2009) with higher biodegradation rates in natural environments could offer a promising development route and opening for a broader use in textile applications. Nevertheless, as biodegradation in soil is set as a crucial EOL option for clothing, the balance between re-use via washing and biodegradation (prevention of plastic accumulation due to abrasion during washing) will be a crucial design parameter. In this light, the use of non-thermoplastic natural fibres such as Viscose or Lyocell could be considered as they are biodegradable in different environments. However, recycling into new high performance textiles might pose a challenge in order to embed these materials into a circular materials economy.

Elastic products are the final and most challenging product category that is investigated with the selection tool described in this study. Assessment of the results shows that only for the product with the least stringent conditions (footwear) PBSA, PBAT and PCL can be defined as circular alternatives. For gloves and tyres it follows that especially the elongation at yield requirement is difficult to match by the selected (thermoplastic) materials. Materials that score better at this specific property (e.g. TPU, but also the currently used non-thermoplastic natural or synthetic rubbers) do not pass the EOL requirements as chemical recycling is not feasible and they will accumulate in the natural environment (due to a lack of biodegradation in nature) which is a fundamental concern for tyre applications specifically. Research in biodegradable TPUs gained a lot of interest in the last decades (Knight et al., 2008; Moravek et al., 2010; Tan et al., 2015), however, these new materials often do not meet the mechanical requirements for more demanding applications like tyres. Therefore, research and development efforts on the development of circular solutions are especially required for this class of materials.

An overview of the most promising polymers per product category and those that are in range of development as identified by the selection tool described in this study is given in Fig. 3. This overview could serve as blueprint for a biobased and circular plastic landscape in 2030. It must be stressed that the output listed in Fig. 3 is the result of the specific and stringent input and boundary conditions that were set for a circular materials economy in 2030. These parameters could change upon new insights, technology progression and legislative measures which will also change the output of the selection tool.

Interestingly, the most promising polymers listed in every category in Fig. 3 are currently not entirely produced from biobased resources, so further research and development has to be performed on this aspect specifically. There are a number of fully biobased polymers (PHB, $PHBV_2$, $PHBH_6$ and PLA) that are currently in the development range of a number of product categories.

The analysis performed in this study and the resulting overview in Fig. 3 show that a substantial amount of the functionality that is currently being supplied by fossil-based plastics can be obtained by (partially) biobased polymers that are currently on or approaching the market. However, especially for barrier plastics (packaging) and elastic plastics a substantial gap has to be bridged in order to meet the basic

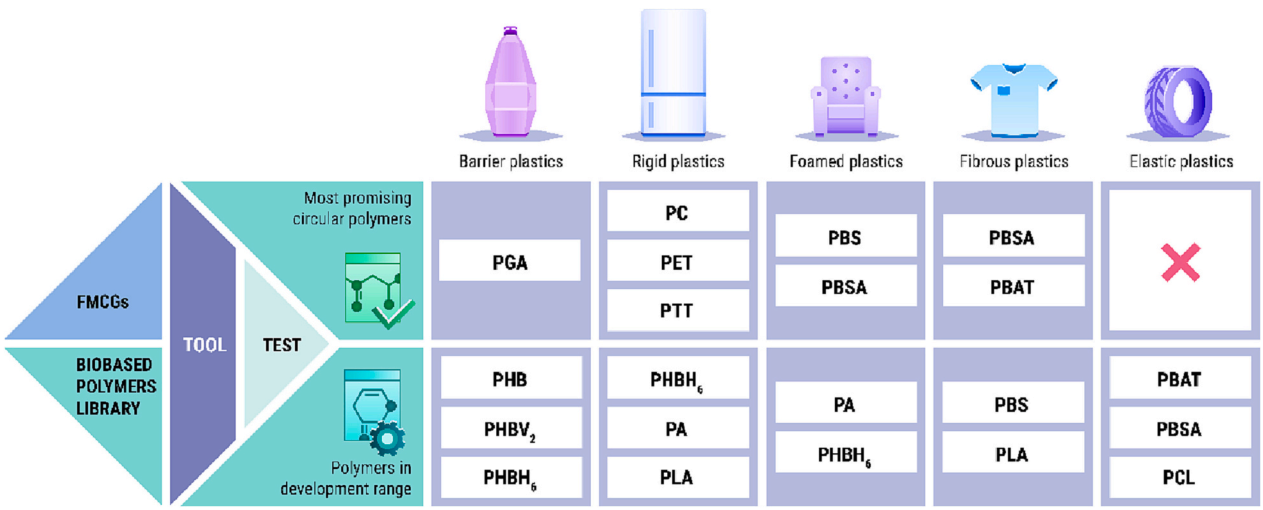

Fig. 3. Summary of most promising materials and materials in development range for each of the product categories investigated in this study. FMCGs: fast moving consumer goods, PGA: poly(glycolic acid), PC: polycarbonate, PET: poly(ethylene terephthalate), PTT: poly(trimethylene terephthalate), PBS: poly(butylene succinate), PBSA: poly(butylene succinate-*co*-adipate), PBAT: poly(butylene adipate-*co*-terephthalate), PHB: poly(hydroxybutyrate), $PHBV_2$: poly(3-hydroxybutyrate-*co*-3-hydroxy-valeriate) with 2 mol% 3 HV, $PHBH_6$: poly(3-hydroxybutyrate-co-3-hydroxy-hexanoate) with 6 mol% 3HH, PA: polyamide, PLA: poly(lactic acid), PCL: polycaprolactone.

functional requirements for products within this category. This gap can be bridged by continued research and development of these materials, but could also be achieved by accepting a decrease in functional performance. As long as general aspects as human health, prevention of food waste, and safety and energy usage are taken into account, a small loss in product performance might be a worthwhile sacrifice for a circular materials economy. In addition, this selection tool only considers to interchange fossil-based plastics by biobased plastics, but does not take into account the option to replace plastic applications by other materials such as wood, cardboard, natural fibres, metal or glass.

Another factor that needs to be considered is the waste management infrastructure. This is currently tailored to and optimized for the processing of fossil-based plastics. Investigations are required that determine to what extent the current mechanical recycling infrastructure can process the materials that are identified here as the most promising circular alternatives. Nevertheless, recycling of biobased polymers via a depolymerization route appears to be inherently more attractive, since it allows the production of recycled polymers with virgin quality. At present, infrastructure for large scale depolymerization of polyester (e.g. PET) waste is still relatively small, but is also expected to expand quickly in the coming decades. The remaining challenge is to set-up the collection and sorting infrastructure to obtain biobased polymer waste streams that can be depolymerised, purified with new to be developed separation technologies and recycled back into biobased polymers. Industrial composting and anaerobic digestion facilities could then act as contingency solutions for waste biomaterials that are highly polluted with organic waste that can no longer cost effectively be recycled.

Next to the technical adaptations to our materials economy, a stronger push from the legislative bodies within Europe is required to make sure that the biobased circular alternatives identified are being favoured over their fossil-based counterparts. In addition to a more fair taxation of carbon dioxide emissions released into the environment, legislation should also demand the integration within existing recycling schemes (solving the recycling lock-in) and enable the use of biodegradable plastics in applications where littering cannot completely be prevented. In order to facilitate this process, the scientific community needs to define more universal methods to quantify whether a material will accumulate in the natural environment or not. In this study ASTM G160-12(2019) has been used to quantify this aspect, but it is likely that this standard is too strict for this purpose and that a number of materials, such as PBS and PLA, are now being assessed too rigorously on this specific parameter. A well-performing consumer good made from a polymer with mediocre biodegradation rate might be preferable over a poorly-performing consumer good made from a polymer which quickly biodegrades, as long as the reduced biodegradation rate doesn't result in the accumulation of microplastic particles in the open environment.

A final consideration that has to be factored in for a successful transition towards a circular plastics landscape is the feedstock that is required for production. Feedstocks for biobased polymers should ideally not compete with food production and adhere to principles of circular agriculture. Although it is anticipated that a small reduction of food waste will already clear sufficient agricultural land for the global biobased material production (vom Berg et al., 2022), research and development efforts should be assigned to the total use of agricultural production. In addition, it should be identified which crops can be locally grown and allow for sustainable and cost-effective conversion into molecular building blocks for industrial biobased polymer synthesis.

The presented strategic selection tool offers an alternative perspective on how we can solve the plastic crises as compared to the more commonly exploited strategies that involve continuation with fossil-based plastics, mechanical recycling and pyrolyzing the resulting plastic waste back to cracker feedstock. The presented perspective of circular biobased economy requires multiple major changes in the industrial landscape of the incumbents, which are not likely to happen spontaneously without strong governmental interventions. The presented perspective can currently not offer the same technical performance for all applications as the fossil-based plastics. But the major advantage over the other strategies is that it does offer a potential solution to curb the negative environmental impacts of plastic waste (climate change, plastic pollution).

5. Conclusions

In conclusion, it is highlighted that the transition towards a biobased circular economy for FMCGs contains multiple barriers of which several have a technical nature. This study has identified several critical technical barriers that need to be addressed in the coming years to enable future progress and curb the negative environmental impacts of plastics. The presented technical selection tool identifies the biobased plastic materials that are required to progress towards a biobased circular economy for consumer goods in 2030. The tool also pinpoints current knowledge gaps. Within this future biobased circular economy all discarded consumer goods need to be processable via all the end-of-life routes they are likely to end-up in. Hence, the objects are reused when feasible, the materials are recycled back into new materials as much as possible with the least amount of spent resources (energy, water, chemicals) conceivable and losses are replenished with renewable feedstocks and do not accumulate in the natural environment. Results are presented for five different product groups (barrier plastics, rigid plastics, foamed plastics, fibrous plastics and elastic plastics). Based on different input parameters, including material functionality and feasibility of waste processing routes, pathways are presented to develop concrete scenarios on the technical design of the circular plastics economy. Based on the selected input, the strategic selection tool demonstrates that at present no biobased circular alternatives exist for most barrier and elastomeric plastics. For fibrous and foamed products a number of plastics that fit the circular demand are currently approaching the market, while for rigid plastic products a relatively wide spectrum of materials is already available at commercial scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.04.005.

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