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Designing with bio-based plastics: guidance for circular product development

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ABSTRACT

The transition to a circular economy calls for reduced reliance on fossil resources. Bio-based plastics offer potential environmental benefits, but their effective use in durable products is complex and under-researched. This study explores key considerations product developers face when using bio-based plastics in circular product development, with a focus on durable applications. Semi-structured interviews with product developers and a scoping literature review were conducted to identify and examine these considerations across the product life cycle. Eight key considerations were derived, highlighting dilemmas related to feedstock selection, regulations, material properties, the mass balance approach, costs, consumer perception, recovery strategies, and biodegradability. The study presents guidance to support product developers in navigating these considerations and making informed decisions. Results highlight the importance of early-stage life cycle thinking and interdisciplinary collaboration. Despite challenges, bio-based plastics can contribute to circular product development when supported by dedicated investments in knowledge and time to, for example, source bio-based plastics with low environmental impact and explore new design opportunities with novel bio-based plastics. The findings offer both theoretical insight and guidance for product developers aiming to incorporate bio-based plastics in their products.

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Bio-based plastics; Product development; Circular economy; Design guidance

1. Introduction

Plastics have become an integral part of our current society, providing a solution across a wide range of applications. When managed properly, they can be a sustainable material choice. Currently, the vast majority of plastics are made from fossil-based resources, contributing to environmental concerns such as carbon emission (Kawashima, Yagi, and Kojima 2019; Rosenboom, Langer, and Traverso 2022). Bio-based plastics (plastics derived partially or fully from renewable feedstocks) can contribute to reducing dependence on fossil resources and align plastic use with circular economy principles. A circular economy aims to ensure that products and materials never become waste and natural systems are

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regenerated (EMF 2019). By storing carbon during their use and recovery phase and releasing it into the atmosphere at end-of-life through biodegradation or incineration so it can be taken up by plants again, bio-based plastics are part of a relatively short-term biogenic carbon cycle (Spierling et al. 2018; Wojnowska-Baryła, Kulikowska, and Bernat 2020).

Despite bio-based plastics currently having a small share in total plastic production, their share is expected to grow (European Bioplastics & nova-Institute GmbH 2024). Furthermore, projections indicate that plastics could account for up to 20% of oil consumption by 2050 (Petroleum Economist 2019), suggesting that material choices made today may have increasing significance in the future. However, bio-based plastics are not inherently sustainable as this depends on factors such as the feedstock sourcing and end-of-life decisions (Ritzen et al. 2024). As a result, integrating bio-based plastics into circular product development introduces new challenges that go beyond simply substituting fossil-based plastics with bio-based alternatives.

Developing products with bio-based plastics entails weighing a range of complex and sometimes conflicting considerations. Although several studies discuss considerations associated with bio-based plastics, e.g. related to environmental assessment, production, material properties and performance, and recovery strategies (Gerassimidou et al. 2021), there is limited guidance to support product developers making informed and sustainable design choices. This is particularly important because product developers play a central role as their decisions influence how products function within circular systems. In this context, product developers refer to all actors involved in the development process, including management at a more strategic level, material scientists, mechanical engineers, product designers and the purchasing department that will source the final materials. Addressing the lack of guidance requires integrated insights from multiple fields such as material science, environmental science, and circular product design.

This study explores key considerations that influence the development of bio-based plastic products within a circular economy. A consideration in this context refers to a dilemma or critical decision point that affects the product development process, such as selecting the bio-based plastic type, balancing durability and biodegradability and addressing the higher material costs of bio-based plastics. These considerations can vary across stakeholders involved in product development (collectively referred to as product developers). The study aims to provide guidance to help product developers address the considerations that emerge throughout the product life cycle. It does not replace existing circular design frameworks but complements them by addressing specific challenges when working with bio-based plastics that are not yet covered in current approaches. Therefore, the research question is: What key considerations do product developers face when using bio-based plastics in the circular development of durable products, and how can they be supported in addressing them?

Literature on bio-based plastic applications focuses mainly on products with a short lifespan, such as packaging, often overlooking the potential and specific challenges of integrating bio-based plastics in durable, long-life products. However, there is already a significant share of durable products on the market that use bio-based plastics, such as household appliances, toys, footwear and automotive parts (European Bioplastics and nova-Institute GmbH 2024), highlighting the lack of research in this area. Therefore, the focus of the study is on the use of bio-based plastics in durable applications. Although other materials, such as natural materials and bio-based composites, also play a role in circular

product design, they are beyond the scope of this study. The study focuses on the European Union, which stems from the fact that most of the companies interviewed in this study were based in Europe, placing the findings in the practical context of product development in the EU.

2. Background: life cycle of bio-based plastics products

In the design of circular products, the entire product life cycle should be taken into account. The life cycle of a material or product is often depicted as a loop going from sourcing to manufacturing, distribution, use and recovery leading back to sourcing. Since a circular economy is never perfect, there will always be an inflow of new materials and energy, as well as some material loss through 'leakage'.

The framework by Ritzen et al. (Ritzen et al. 2023) illustrates the flows of bio-based materials in a circular economy emphasising different material recovery loops (Figure 1). In line with circular economy principles, shorter loops are generally preferred, as they retain product or material value and reduce the need for new resources. Maintenance, re-use, and remanufacturing aim to extend product lifetimes by keeping product in use for as long as possible. Once a product reaches its end-of-life, mechanical recycling, where plastics are physically processed into new products without changes to their chemical structure (CEN 2013), becomes relevant. More advanced techniques such as chemical recycling include dissolution, where polymers are dissolved in a solvent and separated from additives and contaminants; solvolysis, a chemical process that breaks plastics down into their building blocks for reuse; and thermochemical recycling, a process that converts polymers into simpler molecules through high temperatures (Crippa et al. 2019; Ritzen et al. 2023). For biodegradable plastics, the recovery strategies anaerobic digestion (biodegradation in the absence of oxygen) or aerobic digestion (biodegradation in the presence of oxygen) are possible (Ritzen et al. 2023). Finally, incineration is for all bio-based plastics an option to return the materials to carbon dioxide. It implies that incineration in the case of bio-based plastics can be seen as circular, as biological feedstock is used and brought back to simple molecules that are part of the biogenic carbon cycle (Gerassimidou et al. 2021; Parveen, Swami, and Raja 2024; Ritzen et al. 2023). In addition, energy released during incineration and anaerobic digestion can be seen as renewable energy. As the most outer and least value-retaining loop, incineration should be considered a low priority option, also because of the emissions associated with the production, transport and processing of the raw materials and products.

The life cycle of products made with bio-based plastics is shown in Figure 2. It translates the recovery pathways illustrated in Figure 1 into a product-specific life cycle, showing how a product using bio-based plastics can move through the different loops. The life cycle is largely similar to any (plastic) product that cycles in a circular economy, with the exception of the recovery and sourcing phases. As in Figure 1, we distinguish aerobic and anaerobic digestion as specific for biodegradable plastics and have included incineration as an acceptable recovery pathway as the carbon is cycled at a short timescale, in contrast to the carbon release when incinerating fossil-based plastics.

In the sourcing phase, the emphasis shifts to the use of renewable raw materials and energy. Unlike fossil-based plastics which rely on finite resources, bio-based plastics can be derived from, for example, (non)food crops or agricultural residues. Preferably, renewable

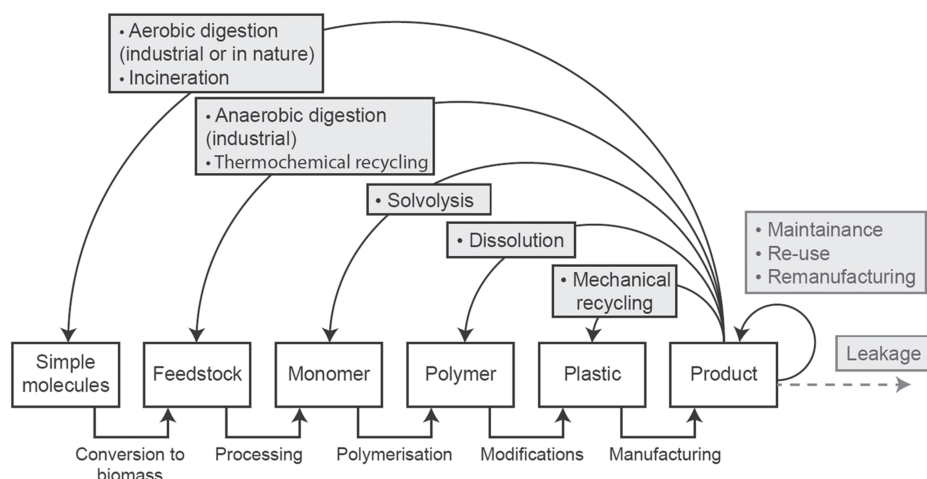


Figure 1. Framework for the circular economy of bio-based plastics incorporated into products by Ritzen et al. (2023). The model shows the continuous material flows in a circular economy.

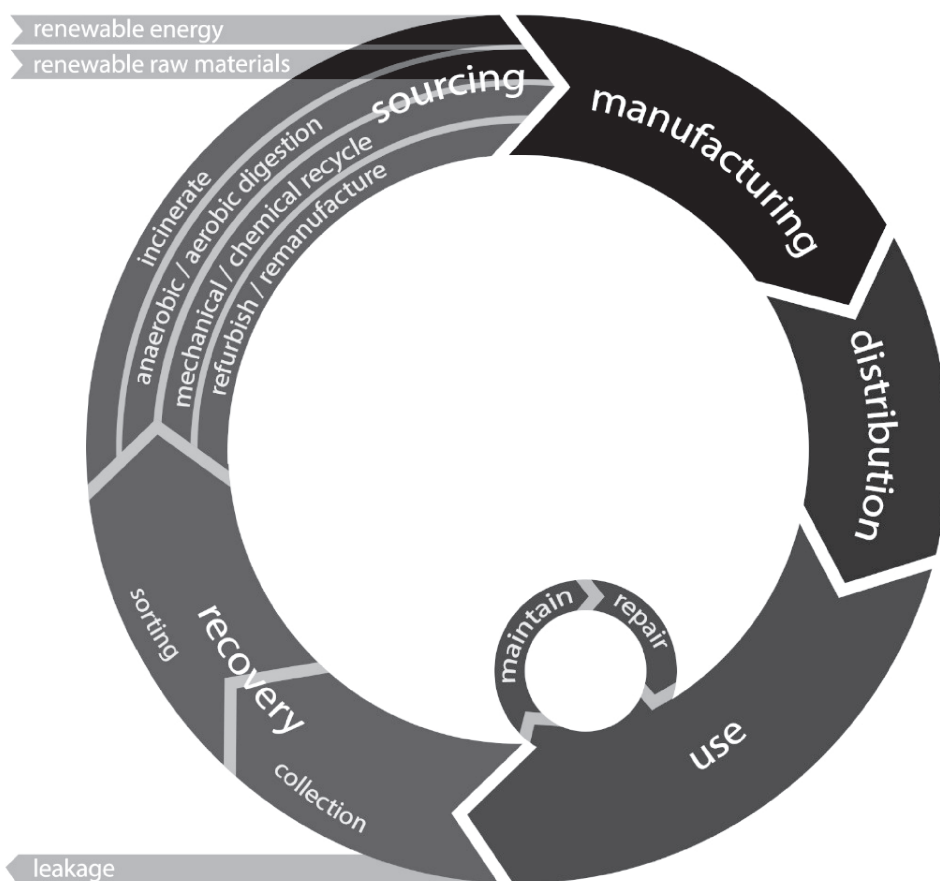


Figure 2. The product life cycle of bio-based plastic products with possible recovery pathways.

energy is used throughout the product life cycle to further reduce the reliance on fossil resources.

While the circular life cycle of bio-based plastics shares much with conventional materials, key differences in sourcing and recovery introduce new considerations for product developers. These differences require new approaches to design and decision-making, which are reflected in the considerations explored in this study.

3. Method

To identify considerations related to the use of bio-based plastics in durable products, interviews with product developers involved in the development of bio-based plastic products, and a scoping literature search were conducted. It is important to note that the interviews were conducted in 2022, while the literature review was completed in 2025. As the bio-based plastics field evolved in this period, the more recent literature provides an updated perspective that enriches the issues raised by product developers during the interviews.

3.1. Interviews

Between March and November 2022 semi-structured interviews with 12 product developers of bio-based plastic products were conducted by the first author. The companies were found by searching Google for bio-based plastic consumer products using keywords such as 'bio-based plastic', 'bio-based polymer, and 'bioplastic' along with 'product' and 'design'. They were included if they developed a durable product with bio-based plastics that was being sold on the European market at the time of the search. Contacting new companies was discontinued after 12 interviews as data saturation was reached, meaning that additional interviews did not provide new insights (Fusch and Ness 2015; Guest, Bunce, and Johnson 2006). Table 1 gives an overview of the interview sample. The participating companies varied in size and covered a broad range of product categories, from toys to furniture. The interviewees' role within the company varied from founders and directors to research and development engineers. This sample allowed different perspectives on the development of durable bio-based plastic products. Two interviews were conducted in person and ten were held online. Each interview lasted approximately one hour. With the participants' consent, all interviews were recorded, transcribed, and anonymised prior to analysis.

To reduce potential interview bias a structured interview protocol was followed. Participants were asked questions about their vision and that of the company, the product, material choice, the design process, end-of-life, the market, and their vision for the future. Questions were formulated in a neutral, non-leading manner and were piloted prior to data collection. The interview results were analysed by the first author using inductive thematic analysis to uncover topics relevant to product developers working with bio-based plastics. Thematic analysis is a method to identify recurring topics and patterns across a text or multiple sources (Vaismoradi, Turunen, and Bondas 2013). The themes relate to one or more stages of the product life cycle and help identify relevant considerations in product development. By speaking directly with practitioners, the interviews provided first-hand insights into the practical challenges and decision points encountered when working with these materials.

Table 1. Overview of the interview sample (I# = interview number, used for quotes in the result section).

I#	Interviewee(s) Position and Geographical Location Western Europe (W-EU) Northern Europe (N-EU) East Asia (E-Asia)	Company Size Small (< 10) Medium (10-100) Large (> 100)	Product Category	Bio-Based Plastic Type* Dedicated (D) Traceable Drop-in (T) Biomass Balance (B)
1	Product designer (W-EU)	small	Household appliances and utensils	PE (T)
2	Co-founder, creative director, product designer (W-EU)	small	Household appliances and utensils	PLA (D)
3	Founder, operational manager (E-Asia)	small	Toys and sports, Information and communication	PLA (D)
4	Chief Executive Officer (CEO) (N-EU)	large	Household appliances and utensils	PA (D)
5	Head of Materials (N-EU)	large	Toys and sports	PE (T)
6	Head of R&D (W-EU)	large	Stationary and drawing	PHA (D)
7	Production manager (N-EU)	small	Personal effects	PLA (D)
8	1. CEO, 2. Product engineer (W-EU)	medium	Toys and sports	PE (T)
9	Material and innovation developer (N-EU)	large	Furniture	PE (T)
10	Circular Sustainability Manager (N-EU)	medium	Household appliances and utensils, Toys and sports	PE (T)
11	Sustainability Leader (W-EU)	large	Household appliances and utensils	TPE (T)
12	Group leader** (W-EU)	large	Personal effects	PP (B)
				PA (D)

* The bio-based plastic types are explained in the Sections '4.3 Consideration 3' and '4.4 Consideration 4'.

** The interviewee works at a material supplier of a bio-based plastic product from the design analysis.

3.2. Literature review

Insights from the interviews revealed several recurring topics. To build on these findings, a scoping literature review was conducted in Scopus in February 2025. The aim was to deepen understanding of the interview topics and identify additional ones relevant to developing products with bio-based plastics.

The following search string was used: TITLE ('biobased plastic*' OR 'bio-based plastic*' OR 'bioplastic*' OR 'bio-plastic*' OR 'biopolymer*' OR 'bio-polymer*' OR 'bio-based polymer*' OR 'biobased polymer*' OR 'biobased product*' OR 'bio-based product*' OR 'biobased and biodegradable plastic*' OR 'bio-based and biodegradable plastic*' OR 'biobased and biodegradable polymer*' OR 'bio-based and biodegradable polymer*') AND TITLE-ABS-KEY (('barrier*' OR 'dilemma*' OR 'challenge*') AND 'product*'). Only journal papers and reviews in English were included.

This search resulted in 593 journal papers and reviews. Our search was conducted in four main phases (see Figure 3). Papers were included if they focused on the use of bio-based plastics in product development or provided general insights into bio-based plastics. Studies that did not have this focus but were instead solely about biodegradable plastics or focused on the chemistry of polymers, plastic manufacturing challenges, or on a specific type of plastic or application were excluded to ensure the generalisability of the considerations. A scan of the titles gave a selection of 45 papers and after reading the abstracts, 21 papers remained. After reading the full-text papers, five more papers were excluded because they approached the topic so differently that the findings could not be applied or used meaningfully. The resulting 17 papers were analysed in ATLAS.ti using thematic analysis. The same themes as in the interview analysis were used and new recurring themes were added. The recurring themes (codes in Table 3) were rewritten into key considerations relevant to the development of products with bio-based plastics.

Each identified consideration was further explored using the interview findings and literature from the scoping review, as well as additional literature and other sources (e.g. norms and standards) obtained through snowballing. This served to deepen the understanding of the dilemmas and critical decision points when using bio-based plastics in product development.

The biomass balance approach was not widely discussed in the initial literature review. However, it was included due to its growing significance to product developers when selecting bio-based plastics, as revealed in the interviews. Brief additional research was needed to better understand the state of the art in mass balance. A search was conducted in Scopus using the search string: TITLE ('biomass balance' OR 'mass balance') AND TITLE-ABS-KEY ('plastic*' OR 'polymer*'). This search gave 21 papers, primarily focused on (chemically) recycled plastics, which is also relevant to bio-based plastics as the mass balance principle applies similarly.

3.3. Analysis of considerations

To develop guidance for product developers, the identified considerations were then matched to corresponding lifecycle stages and mapped onto the product life cycle of bio-based plastic products shown in Figure 2. To further structure the analysis, the considerations were also assessed on macro, meso, and micro levels (Table 2). This distinction can

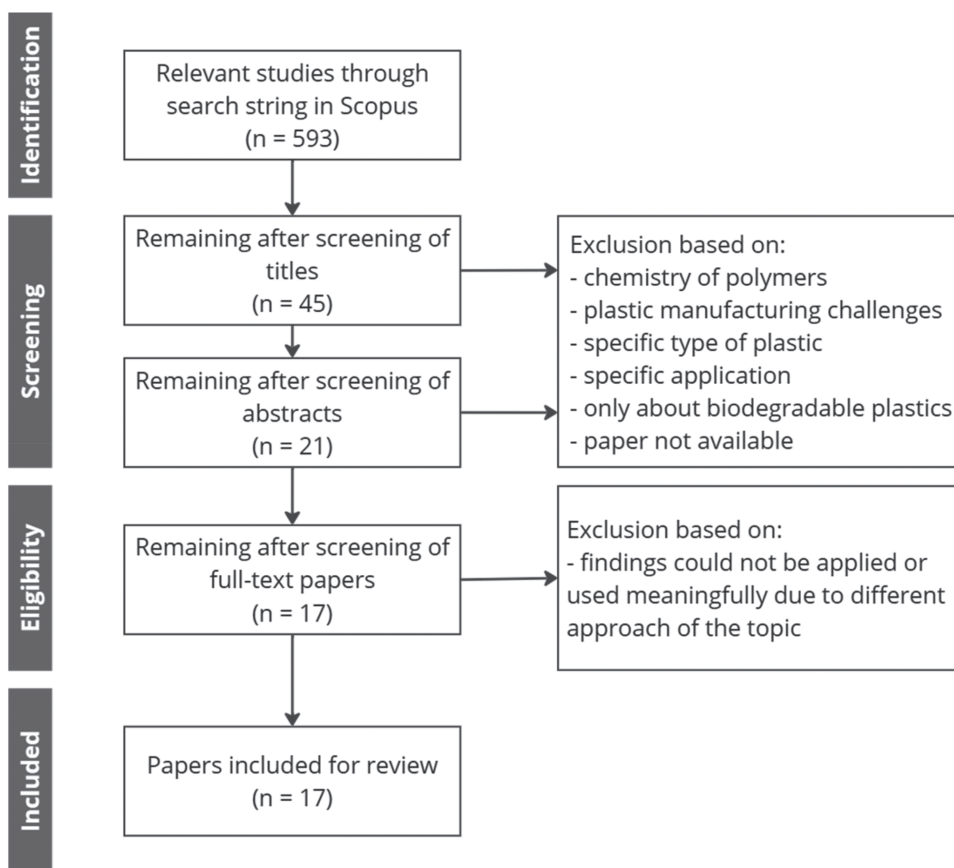


Figure 3. Graphical representation of the literature review search process.

Table 2. Levels in a design project and the influence product developers have.

Macro level: external factors	The context in which the design project is set, e.g., laws and regulations, economic climate, available materials, consumer behaviour.	- Harder to change - Little influence or control by product developers - Product developers have influence and control
Meso level: organization	Strategic decisions within a company, implementation of formal requirements and forming product criteria. E.g., company management.	
Micro level: design process	Product design and engineering decisions, e.g., form giving, material selection.	

enhance the focus and clarity by helping to organise the system (Dopfer, Foster, and Potts 2004): the macro level reflects the broader societal influences such as policy, regulation, and consumer behaviour, the meso level includes the strategies and operations of organisations, and the micro level captures the actions of individuals and product development teams.

By exploring how each consideration influences decision-making across the life cycle and at macro, meso, and micro levels, and by integrating insights from the interviews, literature and other relevant sources, we translated complex dilemmas into guidance. This

guidance is intended to support product developers in designing products with bio-based plastics in a more informed and sustainable way.

4. Considerations when developing durable products with bio-based plastics

The following section presents the key considerations that product developers face when working with bio-based plastics. These were identified through recurring themes in both the interviews and scoping literature review. The codes were then translated into a consideration by identifying the underlying dilemma or critical decisions point faced by product developers. This resulted in several codes forming a single consideration. For example, the codes 'feedstock', 'sustainability' and 'availability' lead to the consideration 'Selecting the most sustainable bio-based plastic'. While 'feedstock' focused on the type and origin of biomass, 'sustainability' addressed its environmental and social impact, and 'availability' reflected concerns about consistent and scalable sourcing. Combined, they highlight the challenge of selecting a feedstock that is both sustainable and feasible in practice.

Table 3 presents the codes and the derived considerations. The results of the interviews were previously published as Bos et al. (2024) and included in Table 3. It shows that all considerations were discussed during the interviews. The scoping literature review identified 16 additional relevant papers discussing considerations when using bio-based plastics in product development. Table 3 presents which topics are addressed in the papers.

Table 3 shows that all the papers discuss sustainability, feedstock, performance, and recovery. One topic that was rarely mentioned in the literature but did emerge during the interviews is mass balance. Also, the topic of drop-in versus novel bio-based plastics is not always addressed in the literature on bio-based plastics. In addition, some papers had specific focus points, e.g. on biodegradation or consumers, whereas these topics were not mentioned at all in others.

The eight identified key considerations from the literature review and interviews were mapped onto the product life cycle of bio-based plastic products by linking each consideration to the specific life cycle stage where it is most relevant or has the greatest impact (Figure 4). For example, consideration 1 is related to feedstock which is associated with the sourcing phase, while consumer perception is related to the user and therefore the use phase. The considerations are summarised in Table 4 and further explained in the text below.

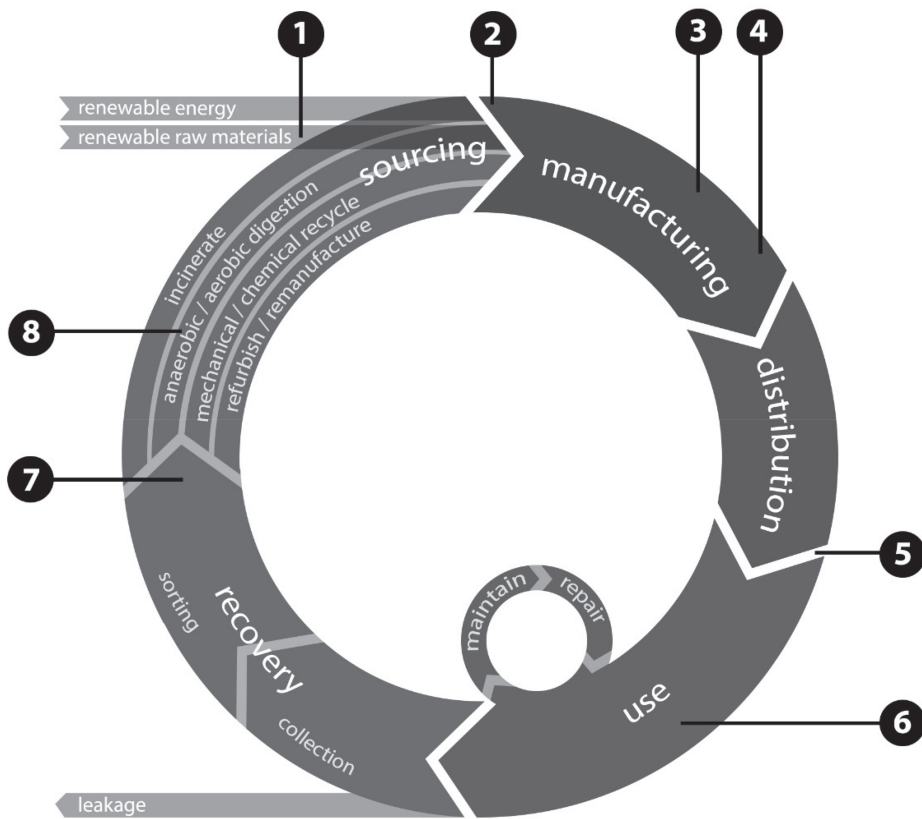
Below, each of the eight key considerations will be discussed in more detail. For each consideration, its relevance within the product life cycle is explained, along with the specific challenges it presents to product developers.

4.1. Consideration 1: Selecting the most sustainable bio-based plastic

Selecting the most sustainable bio-based plastic is not easy. While bio-based plastics are often perceived by the interviewees as more sustainable alternatives to fossil-based materials, their actual environmental and ethical impact depends on a range of factors. The sustainability of a material is often assessed through life cycle assessment (LCA). However, for bio-based plastics, different methods and assumptions (e.g. whether carbon uptake is included) cause a wide variation in results (Parveen, Swami, and Raja 2024; Ritzen et al. 2024;

Table 3. Literature on bio-based plastics and challenges when applying them to products.

[illegible]



- 1 Selecting the most sustainable bio-based plastic
- 2 Prioritizing leadership in bio-based plastic application versus focusing on compliance
- 3 Choosing between straightforward replacement (drop-in plastics) and novel material properties (dedicated bio-based plastics)
- 4 Ensuring traceability of renewable content versus using the biomass balance approach
- 5 Weighing material costs against other values
- 6 Dealing with consumer perceptions
- 7 Balancing product functionality with designing for recovery strategies
- 8 Considering biodegradability in relation to product durability

Figure 4. Eight key considerations when designing with bio-based plastics, mapped across the product life cycle by linking each consideration to the specific life cycle stage where it is most relevant or has the greatest impact.

Rosenboom, Langer, and Traverso 2022), making a fair comparison difficult. Furthermore, the environmental impact of bio-based plastics is heavily influenced by the type of feedstock, its origin, and the manufacturing techniques used (Ritzen et al. 2024; Storz and Vorlop 2013). For example, the research of Ritzen et al. (2024) comparing 31 sourcing scenarios for bioPE, showed that sugar-based biomass, such as sugarcane and sugar beet, generally results in a lower environmental impact compared to starch-based biomass like maize and potatoes. Moreover, the location of cultivation and production (e.g. use of renewable energy) also plays an important role (Ritzen et al. 2024).

Table 4. Considerations when designing with bio-based plastics.

#	Consideration	References
1	Selecting the most sustainable bio-based plastic The sustainability of bio-based plastics depends to a large extent on factors like feedstock type, its origin, and the way the plastic is manufactured. Product developers face challenges in making informed material choices due to limited availability of sustainably and ethically sourced feedstock, and inconsistent LCA data.	(Cardon et al. 2011; Jayakumar et al. 2023; Parveen, Swami, and Raja 2024; Ritzten et al. 2024; Rosenboom, Langer, and Traverso 2022; Storz and Vorlop 2013)
2	Prioritising leadership in bio-based plastic application versus focusing on compliance In an evolving policy landscape where regulations for bio-based plastics remain limited, companies have the choice to meet compliance or show leadership to support sustainability goals and anticipate future trends and regulations.	(Bos et al. 2024; Brockhaus, Petersen, and Kersten 2016; Di Bartolo, Infurna, and Dintcheva 2021; Jayakumar et al. 2023; Melchor-Martínez et al. 2022)
3	Choosing between straightforward replacement (drop-in plastics) and novel material properties (dedicated plastics) Product developers selecting bio-based plastics must choose between drop-in options, which are straightforward to integrate into existing systems as they can directly replace fossil-based equivalents, and dedicated plastics, which offer new properties and environmental benefits but initially require more time, investments, and new infrastructure for recovery and recycling.	(Bos et al. 2024; Carus et al. 2017; IfBB 2021; Ismagilova et al. 2023; Rinke Dias de Souza et al. 2024; Storz and Vorlop 2013; Xia et al. 2021)
4	Ensuring traceability of renewable content versus using the biomass balance approach Product developers increasingly encounter plastics produced using a biomass balance approach, which allocates bio-based content via bookkeeping rather than actual physical content. While this approach may support scalability and cost reduction, it raises concerns about misleading claims and adds complexity to material selection due to limited transparency.	(Beers et al. 2022; Daphne and Ahmed 2024; Schumacher and Beers 2024)
5	Weighing material costs against other values The higher costs of bio-based plastics compared to fossil-based alternatives can be a barrier. However, they may offer added value through new material properties, environmental benefits, alignment with sustainability goals, and potential marketing advantages if 'green' marketing does not turn into greenwashing.	(Bos et al. 2024; Brockhaus, Petersen, and Kersten 2016; Parveen, Swami, and Raja 2024; Storz and Vorlop 2013)
6	Dealing with consumer perceptions Many consumers perceive bio-based plastics as sustainable and safe, although this is not inherently true. Inconsistent terminology and misleading claims contribute to confusion.	(Bos et al. 2024; Findrik and Meixner 2023; Fletcher et al. 2021; Jayakumar et al. 2023; Kymäläinen et al. 2022; Parveen, Swami, and Raja 2024; Shevchenko et al. 2022; Zimmermann et al. 2020)
7	Balancing product functionality with designing for recovery strategies Designing for recovery strategies like recycling and biodegradation influence material choices and product design. Adapting product design to meet recovery goals may negatively affect functionality, cost, or sustainability, requiring a careful balance between all aspects.	(Brockhaus, Petersen, and Kersten 2016; Ritzten et al. 2023; Rosenboom, Langer, and Traverso 2022)
8	Considering biodegradability in relation to product durability Biodegradability can be a valuable recovery option for certain applications, however, navigating between durability and temporality can be challenging. Furthermore, ensuring that materials fully biodegrade in real-world conditions, without contributing to microplastic pollution, presents a significant challenge.	(CEN 2000; ECN 2018; Gerassimidou et al. 2021; Gross and Kalra 2002; nova-Institute GmbH et al. 2021; Rosenboom, Langer, and Traverso 2022; UNSD 2018)

The use of bio-based feedstocks raises ethical concerns, particularly regarding their potential competition with food production (Cardon et al. 2011; Jayakumar et al. 2023; Rosenboom, Langer, and Traverso 2022; Storz and Vorlop 2013). Most commercially available bio-based plastics currently rely on first-generation feedstocks, which are edible crops (Lambert and Wagner 2017; Sheldon and Norton 2020). Currently, only 0.02% of the world's agricultural land is used for the production of bio-based plastics (Melchor-Martínez et al.

2022), however, this will increase as the share of bio-based plastics, which is currently 0,5% of the world's plastic production, grows (European Bioplastics & nova-Institute GmbH 2024). Although scientific data on the actual competition with food supply is lacking, ethical and ecological concerns (e.g. water use and deforestation) are evident (Brockhaus, Petersen, and Kersten 2016; Helm, Venier-Cambron, and Verburg 2025; Rosenboom, Langer, and Traverso 2022). Second-generation feedstocks, which include non-edible crops like castor beans, wood, and residual food waste, offer a more ethically responsible alternative if they are not grown on arable land intended for food cultivation (Jayakumar et al. 2023; Rosenboom, Langer, and Traverso 2022). However, the general lower sugar content of second generation feedstock may require larger quantities to produce the same volume of plastic, potentially increasing their environmental impact (Alalwan, Alminshid, and Aljaafari 2019). Third-generation feedstocks, such as algae, are promising but remain in the early stages of development and have limited availability (Alalwan, Alminshid, and Aljaafari 2019). The overall availability of bio-based plastics remains low due to limited production capacity and supply chain constraints (Abrha et al. 2022; Fletcher et al. 2021; RameshKumar, Shaiju, and O'Connor 2020). Moreover, the currently limited choice in type of feedstock and origin often leaves product developers with few alternatives.

4.2. Consideration 2: Prioritizing leadership in bio-based plastic application versus focusing on compliance

Companies need their materials and products to at least comply with the laws and regulations of the regions where they operate. For product developers working with bio-based plastics, this often involves navigating a policy landscape that is still in development. While there are no binding regulations specifically targeting bio-based plastics yet (Jayakumar et al. 2023; Melchor-Martínez et al. 2022), the EU has introduced a policy framework clarifying aspects of bio-based, biodegradable and compostable plastics, aimed at creating supportive conditions to ensure that the environmental impact of their use is positive (European Commission 2022b). However, existing directives are only focused on short-lived applications (European Commission 2022a). Compliance thus sets limited targets from a sustainability perspective, for example with regard to the amount of bio-based plastic used and the minimum amount of renewable feedstock that must be used to be able to label a plastic as bio-based.

In the absence of strict regulation, companies are faced with a choice: either do the minimum required to remain compliant or be pro-active and show leadership by going beyond the minimum requirements, setting an example for others. This can include using bio-based plastic which are more expensive than conventional fossil-based plastics even though it is not mandatory. Companies showing leadership tend to have more comprehensive sustainability ambitions. For example, there are start-ups with a sustainability vision focusing entirely on products made from bio-based materials and big companies like LEGO and IKEA using bio-based plastics for a part of their portfolio (Bos et al. 2024). In this way they meet internal sustainability goals, strengthen their brand identity and possibly anticipate future regulations.

Meanwhile, the interviews conducted revealed that uncertainty about future regulations is holding some businesses back from investing more heavily in bio-based plastics. While some express an interest in the material and feel incentivized to monitor developments,

they do not feel the urge to take a leading role or act as early adopters (Brockhaus, Petersen, and Kersten 2016).

Leadership can be shown not only in the use of bio-based plastics, but also in their recovery. Current regulations provide guidance, but do not always reflect reality. For instance, standards on biodegradation in nature do not always reflect actual conditions (Di Bartolo, Infurna, and Dintcheva 2021). Some companies take an extra step by testing the biodegradation of their products in a realistic use environment. For example, Senbis produces ropes for the marine environment and is a frontrunner for testing the aerobic biodegradation of the final product in aqueous environments, in accordance with ISO14851 (Senbis n.d.).

4.3. Consideration 3: Choosing between straightforward replacement (drop-in plastics) and novel material properties (dedicated bio-based plastics)

During the manufacturing phase of the product life cycle, product developers must ensure that their selected materials are compatible with production processes. When working with bio-based plastics, they face a key consideration: opting for straightforward replacement of fossil-based plastics with drop-in bio-based plastics or exploring novel material properties offered by dedicated bio-based plastics, which require modifications to manufacturing processes.

Drop-in bio-based plastics are chemically identical to their fossil-based counterparts, allowing straightforward integration into existing production processes and recycling streams (Carus et al. 2017; IfBB 2021). Interviewees indicated that it enables product developers to design as they are used to without needing to invest in new knowledge or alter manufacturing practices (Bos et al. 2024). An example is the plant parts of LEGO, where LEGO replaced PE with bio-PE (Figure 5) (LEGO group 2018).



Figure 5. LEGO plant parts made of bio-PE (LEGO group 2018).

Dedicated bio-based plastics, on the other hand, have no fossil-based equivalent, but are distinct polymers with unique compositions. These offer novel properties that may better suit specific applications or provide environmental advantages (Ismagilova et al. 2023; Rinke Dias de Souza et al. 2024; Storz and Vorlop 2013; Xia et al. 2021). For example, the Skarvan Biobased Pants of Vaude (Figure 6) are made of the dedicated nylon PA6.10, which is lighter (it has a lower density) and has higher fibre strength than fossil-based PA (lower Young's modulus and higher elongation at break) (Vaude 2020). However, the interviews and literature showed that adopting dedicated plastics often requires time and investments during the transition phase, as product developers need to acquire new knowledge about their performance and processing characteristics. Because this knowledge is not yet fully established and practical experience is limited, uncertainties about the behaviour of these newer materials remain, causing product developers to stay sceptical about the durability and performance of bio-based (Bos et al. 2024; Brockhaus, Petersen, and Kersten 2016; Fletcher et al. 2021), which can discourage their adoption. Additionally, designing for recyclability can be challenging when dedicated bio-based plastics are selected, since established recovery and recycling infrastructure for new types of plastic is often lacking (Storz and Vorlop 2013; Terzopoulou and Bikiaris 2024). This applies mainly to the early market phase when volumes are still low. There is also an opportunity to make diverse polymers with limited number of monomers that can be recovered into monomers with chemical recycling, however, the infrastructure and scale need further development.



Figure 6. Vaude Skarvan Biobased Pants made of PA6.10 (Vaude 2020).

From an environmental perspective, the production of dedicated bio-based plastics is likely to be more efficient than that of drop-in plastics (Storz and Vorlop 2013). For example, the widely used drop-in plastic bio-PE relies on converting sugar into ethanol, a process that is relatively inefficient in biomass use (Sara, Brar, and Blais 2016). In contrast, dedicated bio-based monomers use the carbon present in the biomass more efficiently (Cheng et al. 2012; Sara, Brar, and Blais 2016).

The choice between using drop-in or dedicated bio-based plastics requires careful consideration of all these aspects. Product developers play a critical role in this decision-making process, as they are in the position to evaluate not only technical compatibility, but also environmental impact and design and manufacturing opportunities that dedicated and drop-in bio-based plastics may bring.

4.4. Consideration 4: Traceable bio-based plastic vs. biomass balance approach

When product developers choose a drop-in bio-based plastic, the interviewees mentioned they are increasingly presented with the option to choose plastics produced through the biomass balance approach. Traditionally, bio-based plastics are defined by their composition, being made fully or partly from renewable feedstock. The proportion of bio-based content is known and traceable. In contrast, some plastics are labelled as 'bio-based' through a 'biomass balance approach' bookkeeping system, rather than the actual composition of the final product (Schumacher and Beers 2024). This seems an attractive option as it has the advantages of drop-in plastics (it can replace conventional plastics directly) and is often only slightly more expensive than conventional plastics. However, a deeper look at the mass balance approach (often called biomass balance in the context of bio-based plastics) reveals that it can be misleading for a number of reasons, which are discussed below.

In the biomass balance approach, there are different ways of allocating the bio-based content. Typically, these plastics are produced in a steam cracker. The input consists mainly of oil and in addition some bio-based (waste) material is added (e.g. used vegetable oil). The process results in hydrocarbon substances, ranging from ethylene, propylene and monoaromatics for the production of plastics, to olefines that are used for fuels. The proportion of bio-based feedstock entering the steam cracker is then allocated to a proportion of the outputs via certified mass balance schemes. Different allocation schemes can be distinguished (Beers et al. 2022; Daphne and Ahmed 2024). In proportional allocation, bio-based credits are equally distributed over the output compounds, such as high-grade polymers or residues like fuel. In the proportional free allocation method, part of the products may be sold as 100% bio-based while the remaining percentage may be sold as 0% (Beers et al. 2022; Daphne and Ahmed 2024). For example, if the polymer has 30% allocated bio-based content, 30% of the products could be sold as 100% bio-based. Free allocation allows bio-based content to be freely distributed across all outputs, meaning all credits could be attributed to high-grade polymers and none to fuel (Beers et al. 2022; Daphne and Ahmed 2024). In most of these methods, the biomass content in a product doesn't correspond with the claimed content, but is in reality much lower as a weight-percentage of the product. The term bio-based plastics is thus easily misinterpreted, especially when consumer-facing. That this is offset by some of the biomass-containing material being sold as 0% bio-based does not make the practice any less lacking transparency and traceability. The plastic placed

on the market is still being presented as far more sustainable than it actually is, and sold at a premium price. A term that is increasingly used for mass balance plastics is bio-attributed plastics, which might be considered equally misleading if the actual bio-based content of a product is not transparently reported, as it still implies the material itself contains bio-based content.

The mass balance approach is used in other industries, but its application in the plastic industry seems significantly more apt to misinterpretation. For example, while Fairtrade products also use mass balance, their guidelines are strict to prevent misleading claims. Fairtrade does not allow credit schemes; claims must reflect the actual average percentage (Fairtrade International 2020). On the other hand, mass balance based recycled content is dealt with in a similar way as bio-based mass balance. This approach has been framed as deceptive by United States Environmental Protection Agency (2023): *‘Allowing producers to advertise that a product contains ‘recycled content’ based on the amount of recycled material purchased is deceptive. It would be clearer to focus on calculations that involve the actual amount of material used’*.

4.5. Consideration 5: Weighing material costs against other values

During the distribution phase of the product life cycle, the choice of material plays a role in determining both product pricing and brand positioning. Literature indicates that bio-based plastics are often more expensive than fossil-based alternatives, and the interviews confirm that these higher costs represent an important barrier for product (Bos et al. 2024; Brockhaus, Petersen, and Kersten 2016; Storz and Vorlop 2013). For example, the relatively cheap fossil-based PP costs around 1 €/kg and one of the most affordable bio-based plastics PLA costs significantly more with 1,5-2,5 €/kg (Rosenboom, Langer, and Traverso 2022; Schick et al. 2024). Also, drop-in plastic bio-PE costs around 30% more than its fossil-based counterpart PE (Rosenboom, Langer, and Traverso 2022b; Siracusa and Blanco 2020). The costs are relatively high because of factors like limited production scale, more complex manufacturing processes, and potential fluctuations in feedstock availability (Parveen, Swami, and Raja 2024; Storz and Vorlop 2013). Additional expenses may also arise from the need to establish new production processes or supply chains, especially when working with dedicated bio-based plastics.

Despite these higher upfront costs, bio-based plastics can offer added value such as new material properties, reduced environmental impact, alignment with sustainability goals, and potential marketing advantages. However, there is a risk that focusing too much on marketing value, using terms like ‘green’ and ‘sustainable’ without substantiation and transparent and clear information, rather than sustainability goals could lead to greenwashing (Parveen, Swami, and Raja 2024).

4.6. Consideration 6: Dealing with consumer perceptions

For product developers, navigating consumer perceptions of bio-based plastics presents both challenges and responsibilities. During the use phase in a product’s life cycle, consumers engage with the product and the information communicated about it. Misleading marketing claims have contributed to the consumer perception that bio-based plastics are sustainable, safe, and fully biodegradable (Findrik and Meixner 2023; Parveen, Swami, and

Raja 2024). These claims can be deliberate (greenwashing) or may have been the result of widespread misunderstanding of the properties of bio-based plastics among product developers, which also emerges from the interviews (Bos et al. 2024; Goel et al. 2021; Parveen, Swami, and Raja 2024). Product developers work in a context where terminology is confusing, clear regulation is still evolving (see consideration 2), and scientific data is sometimes insufficient to substantiate claims (see consideration 1).

Product developers hold a key position in shaping how products are framed and understood by consumers. Their choices about how materials and sustainability aspects are communicated influence consumer perception. Misconceptions can lead to unintended consequences or unrealistic expectations. For example the misconception that bio-based plastics are always biodegradable (Anderson and Shenkar 2021; Findrik and Meixner 2023; Parveen, Swami, and Raja 2024) and that biodegradable infers under natural circumstances rather than industrial composting, can lead to issues such as contamination in recycling streams or natural environments (Fletcher et al. 2021; Parveen, Swami, and Raja 2024). Additionally, consumers associate terms like ‘natural’ and ‘bio’ with safety and health benefits, even when there is limited scientific evidence to support these claims (Kymäläinen et al. 2022). This gap between perception and performance influences how products are received and can shape both consumer behaviour and market expectations.

4.7. Consideration 7: Balancing product functionality with designing for recovery strategies

Recovery strategies, such as recycling or biodegradation, have an influence on material selection and product design. These strategies often place restrictions on the use of certain materials, additives, and coatings, especially when the goal is to ensure compatibility with established recovery systems (Ritzen et al. 2023). For example, designing for recyclability may require avoiding certain additives or material blending that could complicate the recycling process (Rosenboom, Langer, and Traverso 2022). Similarly, biodegradable plastics only degrade under specific environmental conditions, such as a minimum temperature, which limits the range of suitable materials and additives.

Balancing functional performance with recovery compatibility requires careful alignment between design priorities and sustainability goals. In some cases, optimising for a recovery strategy may compromise other aspects, such as functionality or environmental performance.

4.8. Consideration 8: Considering biodegradability in relation to product durability

In many cases, the considerations for product developers for recovery routes, such as reuse or recycling, are similar for bio-based plastics and conventional materials. However, one property more often found in bio-based plastics is their potential for biodegradability. From a product life cycle perspective, biodegradability of bio-based plastics offers a circular recovery route by recovering simple molecules, that can subsequently be taken up by plants again and form a relatively short-term biogenic carbon cycle (see Figure 1). As the product and material lose their integrity and there is a chance that methane is produced when exposed to uncontrolled conditions, this is preferably one of the last recovery strategies to consider. However, there are applications, such as plastics that inevitably end up in

nature and cause (micro)plastic pollution, where this could be a suitable recovery strategy (Bos et al. 2026; Calero et al. 2021).

Designing for biodegradability may seem contradictory when aiming for durability. Durable products are defined as those that can be used repeatedly or continuously for a year or longer under normal or average physical usage rates (UNSD 2018). Biodegradation refers to the breakdown of a material by naturally occurring microorganisms such as bacteria, fungi, and algae (Gross and Kalra 2002). This suggests a tension between the longevity associated with durability and the temporality implied by biodegradation. Biodegradation usually requires specific environmental conditions, meaning that a biodegradable plastic is not necessarily a material with a short lifespan under normal use.

There are certification schemes that provide guidance in selecting biodegradable bio-based plastics. While these schemes are not without flaws, they offer a useful starting point for assessing biodegradability in different contexts. For example, standards like EN 13432 on packaging industrial compostability and EN 17033 on biodegradable mulch films set criteria for degradation under controlled conditions. These standards typically focus on material breakdown rates, such as requiring 90% degradation within six months for EN 13432 (CEN 2000). However, they often do not reflect real-world conditions. Biodegradability tests are conducted in specific environments, which may differ significantly from those encountered in practice. For example, marine biodegradability tests are conducted at higher temperatures than those typically found in oceans (nova-Institute GmbH et al., 2021), and industrial composting certifications allow for longer degradation periods than those typically applied in practice (Gerassimidou et al. 2021). Moreover, these tests usually assess the material rather than the final product, and permit certain levels of non-biodegradable content, which can lead to microplastic pollution or the presence of harmful residues.

For product developers, the main challenges lie in navigating between durability and temporality. Biodegradability can offer an appealing recovery pathway when it is verified that they fully biodegrade in the conditions the product is used in.

5. Guidance for product developers

At each consideration, product developers face dilemmas or critical decision points in making suitable and sustainable material and design choices. These can be challenging to deal with, for reasons discussed in the considerations. This section focuses primarily on guidance for product developers at meso and micro levels, i.e. aspects they can influence. Micro level refers to product design and engineering decisions, while meso level includes organisational factors such as strategic decisions within a company. Additionally, this section briefly explores potential future developments at the macro level (broader societal influences such as policy, regulation, and consumer behaviour) that could enable a more sustainable adoption of bio-based plastics. Figure 7 gives an overview of the considerations, guidance for product developers and enablers on macro level which can help product developers during important decisions they have to make in the development process. It raises awareness on important topics and provides initial steps towards making choices, but in most cases no concrete decisions as this depends on the product and context.



Figure 7. Life cycle guide for developing durable products with bio-based plastics. Grey: key considerations and decision points; Blue: guidance for meso- and micro-level decisions (product design and organisational factors); Green: macro-level enablers (external factors), mapped on the product life cycle of bio-based plastic products. The figure highlights important topics and initial steps for decision-making.

5.1. Guidance for product developers – meso and micro level

Many decisions, such as the adoption of sustainable materials, are made at the strategic, i.e. meso level. Without commitment at this level, product developers at the micro level may lack the resources and support needed to act. Transitioning to sustainable designs with bio-based plastics requires time and resources, which depend on investment at the organisational level. Sourcing new materials and building the necessary knowledge and infrastructure take time, but these challenges can be reduced by consistent investment.

The transition to bio-based plastics should be driven by genuine sustainability goals rather than marketing alone, as a focus on marketing gives a risk of greenwashing. To demonstrate a true commitment to sustainability, product developers are encouraged to take leadership by exceeding minimum requirements, such as using fully biodegradable plastics.

Product developers can consider several aspects, for example, it is recommended to prioritise the use of second- and third-generation feedstocks with a low environmental impact. When information about the environmental impact is unavailable, product developers are encouraged to ask their suppliers for more information. The interviews showed that this is regularly done and life cycle assessment (LCA) data is sometimes shared, however, it is often difficult for product developers to interpret them (Bos et al. 2024). If there are LCAs available, it can be valuable to work with LCA experts who then carefully evaluate the results, for example examining how carbon is accounted for to ensure fair material comparisons.

In addition to LCA data, transparency about additives is relevant, especially in the case of biodegradable plastics. Toxic ingredients in plastics that are released during biodegradation may be harmful to the environment or human health and should be avoided. This is particularly relevant when materials are designed to degrade in natural environments.

A related concern is the risk of incomplete biodegradation. Even when materials are marketed as biodegradable, they may not fully breakdown under real-world conditions. This can lead to the formation of microplastics or the persistence of harmful residues in the environment. It is important to carefully consider when biodegradability adds value to a product and in which context the product should biodegrade (e.g. industrial composting facility or in soil) (Rosenboom, Langer, and Traverso 2022). Durable plastic products should never be designed for disposal in nature when more valuable recovery strategies like recycling are possible (Gerassimidou et al. 2021). Nonetheless, there are applications where biodegradability is preferred, for example for (parts of) products that wear and could release microplastics in the environment like tires, shoe soles or fishing nets (Calero et al. 2021). In such cases, it is important to carefully consider the conditions under which the plastic needs to biodegrade and select materials that have been proven to do so. It is also important to recognise that the biodegradable product may break down during use, as these are the same conditions under which the microplastics from wear must degrade. This must be considered in the design of the product, for example by making the biodegradable part replaceable or accepting a shorter lifespan.

Since dedicated bio-based plastics have different properties than conventional fossil-based plastics, it is advisable to include material selection during the early stages of the design process and to design with material properties in mind. This allows product developers to iteratively assess which material is the most suitable and sustainable choice and adjust the product design accordingly. For example, wall thickness and structural requirements can be adapted to align with the material's mechanical properties. However, these adaptations can influence other aspects, such as the usability, aesthetics, costs, or environmental impact (Brockhaus, Petersen, and Kersten 2016).

Additionally, it is advisable to consider the intended recovery pathway from the outset, as the material choice can influence available recovery options and vice versa. Product developers should also define which recovery pathway, such as longevity and reuse or biodegradability, takes priority based on the product's intended lifespan and use. When considering the intended recovery route, also consider the available waste management options and technical feasibility in the region where the product will be used, as these may differ per country (Bos et al. 2024; Fletcher et al. 2021; Parveen, Swami, and Raja 2024).

Consumers often form their views based on non-scientific information such as news reports, social media posts, and personal impressions (Brockhaus, Petersen, and Kersten

2016; Fletcher et al. 2021). This underscores the importance of companies providing accurate and transparent information in their marketing and communication towards consumers. Confusion and misconceptions among consumers and the resulting distrust may actually hinder the growth of bio-based plastics (Bos et al. 2024; Fletcher et al. 2021). Product developers are in the position to translate a complex message into clear, accurate messages for consumers through product and marketing design. By giving clear information about the bio-based plastics used, their environmental impact and the correct way of disposing the product at end of life, they can support more informed consumer behaviour. At the same time, product developers note that too much information, even if correct, can contribute to confusion (Bos et al. 2024). The use of clear and recognised certification labels, such as the universal recycling codes or TÜV Austria's OK biodegradable labels, can provide helpful visual cues (Morone et al. 2021).

Plastics produced using the biomass balance method are becoming more popular among product developers because they offer familiar material properties and established recovery options. However, caution is advised when using these materials, as they can contribute to greenwashing, especially in cases where the reported percentage bio-based differs from the actual amount (e.g. when free allocation is applied). It is therefore advisable for product developers to aim for using traceable bio-based plastics. When this is not possible and biomass balance plastics are considered, product developers should check the allocation practices. Biomass balance plastics with free allocations should be avoided and correct, transparent information should be communicated to consumers.

5.2. Enablers – macro level

Several macro-level factors are expected to drive the broader adoption of bio-based plastics. Policies aimed at promoting sustainable solutions can serve as strong incentives for companies to invest in bio-based plastics (Döhler, Wellenreuther, and Wolf 2022; Parveen, Swami, and Raja 2024). As more countries commit to circular economy goals, there will likely be increased focus on material recovery and more regulations around bio-based plastics. Public funding and other financial incentives can further accelerate this transition (Di Bartolo, Infurna, and Dintcheva 2021; Parveen, Swami, and Raja 2024).

Growing attention to bio-based plastics is expanding the available information for product developers, making it easier to make informed decisions. Advances in material science are expected to lead to the development of improved bio-based plastics and additives, with a bigger supply and likely shift toward more use of second- and third-generation feedstocks. Additionally, increasing global awareness of plastic pollution and the need for sustainable materials is expected to drive new regulations and certification standards, including more realistic biodegradability testing under realistic environmental conditions. Meanwhile, consumers are becoming more educated about sustainability, demanding greater transparency and genuinely sustainable products, which may further push companies toward adopting bio-based solutions.

6. Discussion

The challenges described by the interviewees were largely confirmed by the literature, which offers little contradiction and instead reinforces the knowledge gaps surrounding the

use of bio-based plastics in product development. Product developers aiming to develop products with bio-based plastics face several knowledge gaps throughout the process and need to make design decisions under uncertainty. Sometimes information is not available, such as LCA data, the type of additives that were used, or how bio-based content was allocated in mass balance. Even when such information is available, it can be difficult for product developers to interpret it. This uncertainty can complicate material selection and design decisions. As a result, product developers may become hesitant to work with bio-based plastics or choose to stick to regulatory compliance rather than pursue more ambitious sustainability goals.

This raises the question of whether it should be the responsibility of product developers to fully understand and evaluate all the technical information related to bio-based plastics. While technical knowledge is valuable, product development does not take place in isolation but is embedded in broader organisational and societal systems. Addressing complex challenges requires system-level thinking and efforts across multiple levels and disciplines (Norman and Stappers 2015). In practice, product developers often act as intermediaries between, e.g. material science, policy, and consumer communication. While collaboration should be part of any product development process (Olson, Walker, and Ruekert 1995), it is particularly important when working with bio-based plastics, where there are still many knowledge gaps, and manufacturing processes and waste management infrastructures are not yet adapted.

The decisions made at the micro level, such as material selection and design choices, are largely influenced by strategic decisions made at meso level in a company or organisation. Company goals and the allocation of (financial) resources influence whether product developers have the opportunity to experiment with the use of novel materials like bio-based plastics. Organisations that choose to lead in this area must be prepared to accept a degree of uncertainty and risk, such as availability of the plastics and blank spots in current legislation. For example, current regulations for chemical migration testing in food packaging do not yet account for the potential effects of material ageing in biodegradable plastics, potentially overlooking environmental and health effects (Gerassimidou et al. 2021). This can place an unrealistic burden on product developers, who are expected to navigate technical uncertainties, assess environmental and health impacts, and manage potential regulatory risks. Without adequate support, expecting developers to fully address these challenges may limit the feasibility of implementing ambitious sustainability goals.

The challenges are reinforced by the currently limited contribution of bio-based plastics to overall plastic production. In recent years, the share of bio-based plastics in total plastic production has decreased from approximately 1% in 2022 to around 0.5% in 2024, mainly due to the overall growth in plastic production (European Bioplastics & nova-Institute 2022; European Bioplastics & nova-Institute GmbH 2024). In combination with the fact that plastics currently account for approximately 9% of global oil consumption (Petroleum Economist 2019), the immediate impact of bio-based plastics on reducing fossil resource use appears small. This limited market presence may partly explain organisational hesitation to prioritise bio-based plastics, even though projections suggest that plastics could account for a much larger share of oil consumption in the future, highlighting the importance of making different material choices now.

To manage uncertainties, the literature suggests the value of risk assessments to identify potential risks and risk management strategies to reduce their impact during product

development. Close relationships and collaboration between key actors are ways to manage the risk of uncertainty, however, such collaborations can also introduce risks, such as dependence on a single supplier (Giunipero and Eltantawy 2004). Broader collaborations, such as public-private partnerships and learning environments, have also been identified as ways to reduce both internal and systemic knowledge gaps by facilitating access to current research (Adams 2012; Harris and Lyon 2013). However, they can also reinforce biases; for instance, it was observed that some favourable publications about the mass balance approach were co-authored by stakeholders with vested interests in the approach (Ellen MacArthur Foundation 2019; Jeswani et al. 2019; Krüger et al. 2018).

While this paper outlines key considerations and offers guidance, practical implementation remains challenging. As long as significant knowledge gaps remain, it is difficult to offer uniform recommendations to product developers. Many of the choices they face are shaped by incomplete information, evolving standards, and systemic limitations. At the same time, this study was limited in time in a rapidly developing field. For example, the topic of mass balance approaches would probably be much more prominent in interviews if they were conducted again today, given their increasing industrial uptake. However, it is unclear whether product developers' understanding of these approaches has developed accordingly, as accessible research and clear guidance for practitioners remain limited. Although the use of mass balance plastics may facilitate the growth of renewable feed-stock use within existing supply chains, their widespread adoption may hinder innovation with fully bio-based, dedicated plastics.

On the other hand, governments initiatives such as the Dutch BioBased Circular National Growth Fund programme aim to accelerate the development of a new industry producing traceable, circular bio-based plastics that can compete with established materials (BioBased Circular n.d.). In addition, growing interest in biodesign and regenerative design (Karana, Barati, and Giaccardi 2020) reflects broader ambitions to move beyond straightforward material substitution towards more systemic and circular approaches. Whether these different developments will lead to more sustainable and better-informed choices for product developers remains to be seen. Further progress will therefore likely not only depend on technological innovation, but also on sustained investment at both organisational and systemic levels, and continued efforts to translate emerging knowledge into practical guidance for product developers.

6.1. Limitations and future research

This study provides insights into the use of bio-based plastics in durable applications from a product development perspective, however, it is subject to several limitations.

The analysis focussed primarily on broadly applicable product development considerations and did not go into specific product categories. By concentrating on durable applications, this work did not address the largest current application area for bio-based plastics: packaging (European Bioplastics & nova-Institute GmbH 2024). While many of the insights may also be relevant to short-lived products, future research could examine these applications in more detail. Furthermore, our focus was mainly on the European context, and expanding the scope to include other regions could offer additional insights, for example on recovery infrastructure. An interesting next step for research would be to explore and validate the proposed considerations and guidelines through case studies.

The field of bio-based plastics is changing rapidly, and with it, the perceptions and knowledge of product developers. We have not addressed this change in this work, but it is an interesting direction to explore further in future research. Also, further research is needed to explore how product developers can be effectively informed and supported, for example through decision-support tools. Understanding how the scientific insights we have gained in this work can be translated into accessible and practical guidelines for product developers would enhance the practical impact. In addition, enablers on macro level were identified, but assessing their effectiveness and feasibility was outside of the scope of this research. Research on these identified expected enablers would be an interesting next step and could provide valuable input for the transition to bio-based plastic use.

7. Conclusion

This research explored the key considerations product developers face when using bio-based plastics in the circular development of durable products, and how they can be supported in addressing them. Through interviews and a scoping literature review, the key considerations were identified. The dilemmas associated with the considerations were explored and guidance for product developers was formed to help them deal with these dilemmas.

The findings highlight that while bio-based plastics can contribute to circular design goals, their sustainable implementation requires making several informed choices throughout the product life cycle. This study underscores the importance of embedding life cycle thinking into the early stages of product development. Product developers have to deal with constraints and uncertainties throughout the life cycle, such as limitations in current standards, low availability of materials and misconceptions amongst consumers.

Despite these challenges, bio-based plastics can help the transition towards a more circular economy and less dependence on fossil resources. Many of the current barriers can be addressed through dedicated investments of time and resources by companies and product development teams in, for example, sourcing bio-based plastics with low environmental impact and exploring new design opportunities with novel bio-based plastics. The guidance presented in this study serves as a tool to support informed decision-making and help navigate the complexities associated with the use of bio-based plastics. Using and experimenting with bio-based plastics will accelerate the learning process and support more effective and sustainable integration of bio-based plastic in circular product design.

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Author contributions

CRedit: **Puck Bos:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing; **Sonja Van Dam:** Conceptualization, Methodology, Supervision, Writing – review & editing; **Ruud Balkenende:** Conceptualization, Methodology, Supervision, Writing – review & editing; **Conny Bakker:** Conceptualization, Methodology, Supervision, Writing – review & editing

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Informed consent statement

Informed consent was obtained from all subjects involved in the study.

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