



Delft University of Technology

From Plants to Plastic Products

Bio-based Plastics for Circular Product Development

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Bio-based Plastics for Circular Product Development



Puck Bos

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Bio-based Plastics for Circular Product Development

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To Guus and Bram

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GLOSSARY

Product developer	Stakeholders involved in product development, including management, material scientists, mechanical engineers, product designers, and the purchasing department that will source the final materials
Polymer	A large molecule built up from repeating smaller units called monomers
Plastic	Material that contains a polymer as its essential ingredient and can be shaped by flow during processing into final products [1]
Renewable resource	A natural resource that can regenerate or restore its stock levels over time through natural processes of growth or replenishment [2]
Bio-based plastic	A plastic produced, at least partially, from renewable biological resources [3, 4]
Durable product	Product that can be used repeatedly or continuously for a year or longer, under normal or average physical usage rates [5]
Dedicated bio-based plastic	Bio-based plastics which have a novel chemical structure and do not have an identical fossil-based counterpart (e.g., PLA, PHA, and some PA grades) [6, 7]
Drop-in bio-based plastic	Bio-based plastics with identical chemical structure and properties as their fossil-based equivalent (e.g., bio-PE, bio-PET, and bio-PP) [6, 7]
Biodegradable plastic	Plastics that can be degraded by naturally occurring micro-organisms such as bacteria, fungi, and algae [8]
Ambiently biodegradable plastic	Plastics that break down in the natural environment in a relatively short time frame (days to months, instead of years or longer)
Aerobic digestion	Biodegradation in the presence of oxygen, producing biomass, carbon dioxide, water and mineral salts of any other elements present [9]
Anaerobic digestion	Biodegradation in the absence of oxygen, producing biomass, carbon dioxide, methane, water, and mineral salts of any other elements present [10]
Industrial composting	Aerobic digestion under controlled conditions in an industrial facility
Home composting	Aerobic digestion on small scale, under ambient temperatures
Biomass balance approach	A method that allows the allocation of bio-based feedstock to final products within a shared production system through a certified accounting process instead of physical content [11]

POLYMER ABBREVIATIONS

APC	Aliphatic Polycarbonate
CA	Cellulose Acetate
CP	Casein Polymer
CR	Cellulose Regenerate
EVA	Ethylene-vinyl acetate
PA	Polyamide
PBAT	Poly(Butylene Adipate-co-Terephthalate)
PBS	Polybutylene Succinate
PE	Polyethylene
PEF	Polyethylene Furanoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoate
PLA	Polylactic Acid
PP	Polypropylene
PTT	Polytrimethylene Terephthalate
SCPC	Starch Containing Polymer Compound
TPE	Thermoplastic Elastomers

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SUMMARY

The world is at a critical point where sustainability is no longer an option, but a necessity. The circular economy, based on the principles that products and materials never become waste and natural systems are regenerated, offers guidance for transforming our industrial practices and consumption patterns. It moves us away from the traditional linear model of take, make, and dispose to one where materials circulate and retain their value. Central to this transition is the development of products that are not only made of sustainable materials but also thoughtfully designed to loop back into the economy through, for example, reuse and recycling.

Bio-based plastics offer a promising opportunity in the search for sustainable materials. Derived from renewable feedstocks such as plants and agricultural waste, they offer an alternative to traditional fossil-based plastics. Like their conventional fossil-based counterparts, bio-based plastics can have multiple recovery cycles, such as reuse and recycle. A fundamental difference is that bio-based plastics do not contribute to global warming at the end of their life. When incinerated or biodegraded at the end of life, preferably after several recovery loops, the carbon is released into the atmosphere as part of the biogenic carbon cycle, where it can be taken up by plants again.

Despite their potential, bio-based plastics are predominantly applied in packaging and other short-lived products, and the opportunities of using bio-based plastics in durable products remain largely underexplored. This gap is also reflected in scientific literature, which tends to focus mainly on short-life applications. However, using bio-based plastics in the development of durable, circular products requires more than a one-to-one substitution with fossil-based plastics. It requires, for example, rethinking of how materials are selected, how products function over time, and how they are recovered at the end of use.

This dissertation explored how bio-based plastics can be incorporated into the development of durable products designed for a circular economy. The focus of the research was on the perspective of product developers who are responsible for making strategies and key decisions on, for example, materials, functionality, and recovery strategies. As key actors in shaping product sustainability, product developers play an important role but often face uncertainty when working with novel materials like bio-based plastics.

The dissertation presents four interconnected studies, each offering insights into different aspects of applying bio-based plastics in the design and development of durable, circular products. The first two studies investigated how bio-based plastics are currently used and perceived in durable products, while the latter two explored how they might be applied more effectively.

The first study (Chapter 2) investigated the drivers and barriers to using bio-based plastics in durable products, based on a workshop with stakeholders in the value chain of a telecommunications company. Participants, who had limited experience with bio-based plastics, expressed both enthusiasm and hesitation. While the potential of these materials—such as enabling circular business models, reducing environmental impact, and offering unique properties—is recognized,

concerns about, for example, cost, performance, and lack of information often stand in the way of using them.

While the first study focused on the perceptions among stakeholder with limited experience with bio-based plastics, the second study (Chapter 3) examined the current state of bio-based plastic use in durable consumer products. Through a design analysis of 60 products and 12 interviews with product developers of these products, the study identified opportunities and barriers of bio-based plastic use in durable applications. The findings showed that product developers are motivated to use bio-based plastics as they fit in their sustainable vision and offer, for example, marketing value. However, product developers encountered several barriers like high materials and R&D costs, lack of accessible and reliable information, and uncertainty about the sustainability of the plastics. These findings highlight the need for better education, collaboration, and design guidance to support more informed and creative use of bio-based plastics.

Building on these insights, the third study (Chapter 4) explored the more speculative question if we can use ambiently biodegradable plastics in durable products that wear to reduce microplastic pollution in the environment. Through speculative design explorations of shoes, toothbrushes, and marine ropes, the study introduced new thinking on how biodegradability can be a valuable recovery strategy in contexts where wear and material loss are inevitable. This perspective challenges the traditional association of durability with long-lasting, non-degradable materials, and instead proposes that, in certain cases, biodegradation could offer a more responsible path. The study opens up promising directions not only for sustainable product design but also for materials development, highlighting the need for new types of biodegradable plastics tailored to the specific performance demands of durable products that wear.

To support product developers in navigating the complexities of using bio-based plastics in durable products in a circular way, the final study (Chapter 5) aimed to provide guidance. Drawing on insights from the previous studies and a literature review, it identified eight key considerations that influence the product development process when working with bio-based plastics. The considerations and proposed guidance for product developers to address them were summarized in the life cycle guide in Figure 1. The findings emphasize that the successful and sustainable use of bio-based plastics requires informed decision-making throughout the product life cycle. Embedding life cycle thinking early in the product development process and investing time and resources in knowledge development are important in the transition to developing products with bio-based plastics.

Overall, this dissertation provides guidance for product developers wanting to develop durable, circular products using bio-based plastics. The work shows that the transition to circularity is not only about substituting materials, but also about rethinking how products are designed and developed, balancing multiple aspects such as functionality, durability, recovery strategies, and the environmental implications of material choices.



Figure 1. Life cycle guide for developing durable products with bio-based plastics: considerations (grey), guidance for product developers (blue) and enablers on macro level (green), mapped on the product life cycle of bio-based plastic products.

SAMENVATTING

De wereld bevindt zich op een cruciaal punt waar duurzaamheid niet langer een optie is, maar een noodzaak. De circulaire economie, gebaseerd op de principes dat producten en materialen nooit afval worden en natuurlijke systemen worden geregenereerd, biedt richtlijnen voor het transformeren van onze industriële praktijken en consumptiepatronen. Het haalt ons weg van het traditionele lineaire model van nemen, maken en weggooien naar een model waarin materialen circuleren en hun waarde behouden. Centraal in deze transitie staat de ontwikkeling van producten die niet alleen gemaakt zijn van duurzame materialen, maar ook zorgvuldig ontworpen zijn om terug te keren in de economie door middel van bijvoorbeeld hergebruik en recycling.

Biogebaseerde kunststoffen (bio-based plastics) bieden een veelbelovende kans in de zoektocht naar duurzame materialen. Gemaakt van hernieuwbare grondstoffen zoals planten en landbouwafval, vormen ze een alternatief voor traditionele fossiele kunststoffen. Net als hun conventionele fossiele tegenhangers kunnen bio-based plastics meerdere terugwinningscycli doorlopen, zoals hergebruik en recycling. Een fundamenteel verschil is dat bio-based plastics aan het einde van hun levensduur niet bijdragen aan de opwarming van de aarde. Bij verbranding of biologische afbraak aan het einde van hun levensduur, bij voorkeur na meerdere terugwinningscycli, wordt de koolstof als onderdeel van de biogene koolstofcyclus weer aan de atmosfeer afgegeven, waar het opnieuw door planten kan worden opgenomen.

Ondanks hun potentieel worden bio-based plastics voornamelijk toegepast in verpakkingen en andere producten met een korte levensduur, en blijven de mogelijkheden voor het gebruik van bio-based plastics in producten met een lange levensduur ('durable' producten) grotendeels onderbelicht. Deze kloof komt ook tot uiting in de wetenschappelijke literatuur, die zich vooral richt op toepassingen met een korte levensduur. Het gebruik van bio-based plastics bij de ontwikkeling van circulaire durable producten vereist echter meer dan een één-op-één vervanging van fossiele kunststoffen. Het vraagt bijvoorbeeld om een heroverweging van de manier waarop materialen worden geselecteerd, hoe producten in de loop van de tijd functioneren en hoe ze aan het einde van hun levensduur worden teruggewonnen.

Dit proefschrift onderzoekt hoe bio-based plastics kunnen worden geïntegreerd in de ontwikkeling van durable producten die zijn ontworpen voor een circulaire economie. Het onderzoek richtte zich op het perspectief van productontwikkelaars die verantwoordelijk zijn voor het maken van strategieën en belangrijke beslissingen over bijvoorbeeld materialen, functionaliteit en terugwinningsstrategieën. Productontwikkelaars spelen een belangrijke rol in het vormgeven van de duurzaamheid van producten, maar ze ervaren vaak onzekerheden wanneer zij werken met nieuwe materialen zoals bio-based plastics.

Het proefschrift presenteert vier onderling samenhangende studies, die elk inzicht bieden in verschillende aspecten van de toepassing van bio-based plastics in het ontwerpen en ontwikkelen van circulaire durable producten. De eerste twee studies onderzochten hoe bio-based plastics momenteel worden gebruikt

en ervaren in durable producten, terwijl de laatste twee studies verkenden hoe ze effectiever kunnen worden toegepast.

De eerste studie (Hoofdstuk 2) onderzocht de drijfveren en barrières voor het gebruik van bio-based plastics in durable producten, op basis van een workshop met belanghebbenden in de waardeketen van een telecommunicatiebedrijf. De deelnemers, die beperkte ervaring hadden met bio-based plastics, toonden zowel enthousiasme als terughoudendheid. Hoewel het potentieel van deze materialen—zoals het mogelijk maken van circulaire bedrijfsmodellen, het verminderen van de milieu-impact en het bieden van unieke eigenschappen—wordt erkend, staan zorgen over bijvoorbeeld kosten, prestaties en een gebrek aan informatie het gebruik ervan vaak in de weg.

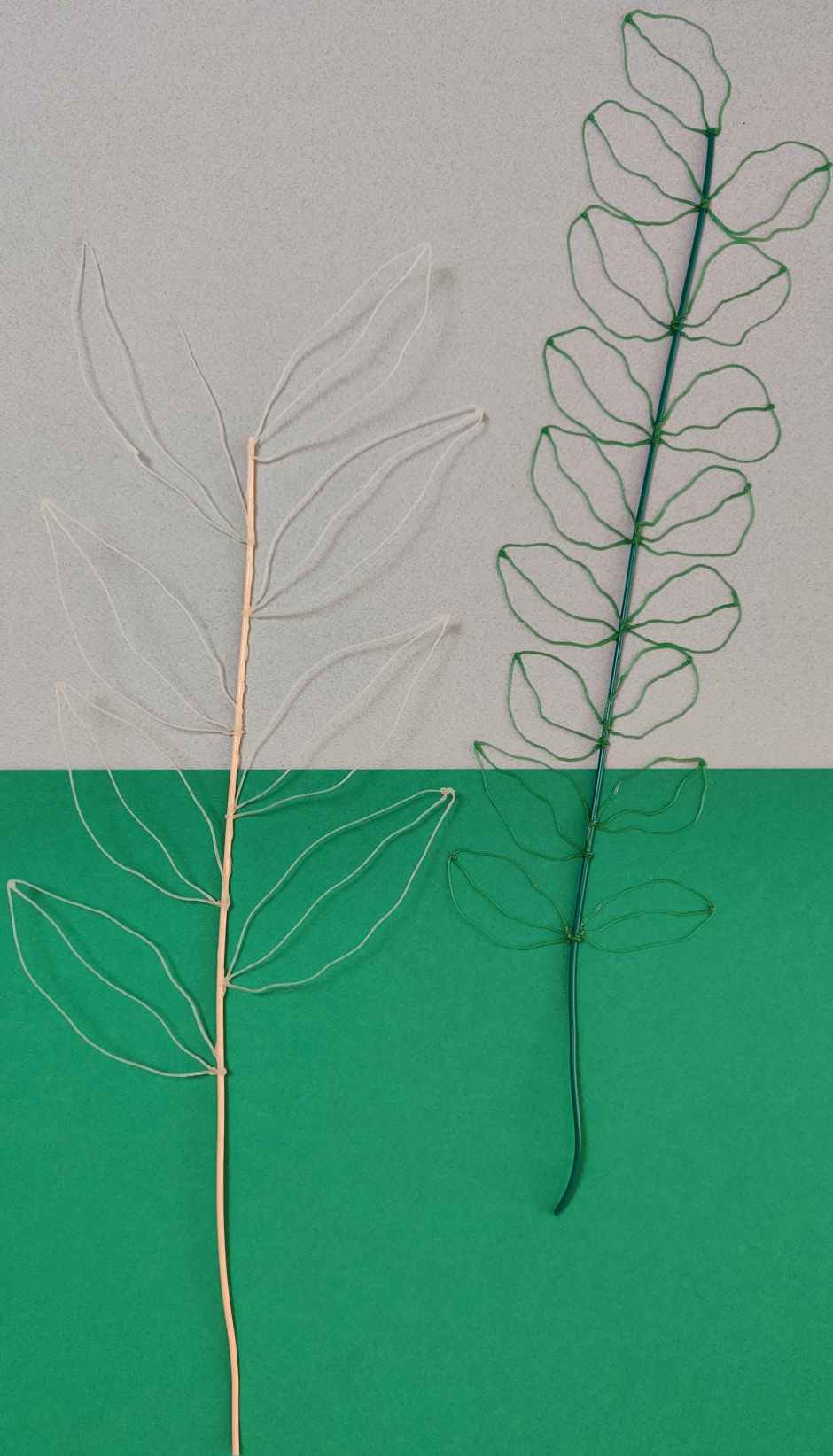
Waar de eerste studie zich richtte op de percepties van belanghebbenden met beperkte ervaring met bio-based plastics, onderzocht de tweede studie (Hoofdstuk 3) de huidige stand van zaken met betrekking tot het gebruik van bio-based plastics in durable consumentenproducten. Door middel van een ontwerpanalyse van 60 producten en 12 interviews met productontwikkelaars van deze producten, identificeerde de studie kansen en barrières voor het gebruik van bio-based plastics in durable toepassingen. Uit de bevindingen bleek dat productontwikkelaars gemotiveerd zijn om bio-based plastics te gebruiken, omdat deze passen in hun duurzame visie en bijvoorbeeld marketingwaarde bieden. Tegelijk stuitten ze op verschillende obstakels, zoals hoge materiaal- en R&D-kosten, een gebrek aan toegankelijke en betrouwbare informatie, en onzekerheid over de duurzaamheid van de kunststoffen. Deze bevindingen benadrukken de noodzaak van betere voorlichting, samenwerking, en ontwerprichtlijnen om een beter geïnformeerd en creatiever gebruik van bio-based plastics te ondersteunen.

Voortbouwend op deze inzichten onderzocht de derde studie (Hoofdstuk 4) de meer speculatieve vraag of we biologisch afbreekbare kunststoffen kunnen gebruiken in durable producten die slijten, om zo de vervuiling van het milieu met microplastics te verminderen. Door middel van speculatieve ontwerpexploraties van schoenen, tandenborstels en scheepstouwen introduceerde de studie een nieuwe manier van denken over hoe biologische afbreekbaarheid een waardevolle strategie kan zijn in contexten waar slijtage en materiaalverlies onvermijdelijk zijn. Dit perspectief daagt de traditionele associatie van duurzaamheid met lang meegaande, niet-afbreekbare materialen uit en stelt in plaats daarvan dat biologische afbraak in bepaalde gevallen een verantwoordelijkere optie kan bieden. De studie opent veelbelovende richtingen, niet alleen voor duurzaam productontwerp maar ook voor materiaalontwikkeling, en benadrukt de behoefte aan nieuwe soorten biologisch afbreekbare kunststoffen die zijn afgestemd op de specifieke prestatie-eisen van durable producten die slijten.

Om productontwikkelaars te ondersteunen bij het navigeren door de complexiteit van het werken met bio-based plastics in durable producten op een circulaire manier, richtte de laatste studie (Hoofdstuk 5) zich op het bieden van handvatten. Op basis van inzichten uit de eerdere studies en een literatuuronderzoek werden acht belangrijke overwegingen geïdentificeerd die het productontwikkelingsproces beïnvloedden bij het werken met bio-based plastics. Deze overwegingen en voorgestelde adviezen voor productontwikkelaars

om hiermee om te gaan, zijn samengevat in de levenscyclusgids in Figuur 1. De bevindingen benadrukken dat het succesvol en duurzaam gebruik van bio-based plastics weloverwogen besluitvorming gedurende de hele levenscyclus van het product vereist. Het vroegtijdig integreren van levenscyclus denken in het productontwikkelingsproces en het investeren van tijd en middelen in kennisontwikkeling zijn belangrijk in de transitie naar het ontwikkelen van producten met bio-based plastics.

Dit proefschrift biedt handvatten voor productontwikkelaars die circulaire durable producten willen ontwikkelen met bio-based plastics. Het werk laat zien dat de transitie naar circulariteit niet alleen gaat om het vervangen van materialen, maar ook om het heroverwegen van hoe producten worden ontworpen en ontwikkeld, waarbij verschillende aspecten zoals functionaliteit, duurzaamheid, terugwinningstrategieën en de milieu-implicaties van materiaalkeuzes tegen elkaar worden afgewogen.



1

Introduction

Product development plays a central role in the transition to a circular economy. The decisions made during this process influence how products function within circular systems, including considerations such as longevity, reparability, reuse, and the selection and recoverability of materials throughout a product's lifecycle. 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. Products made from plastics, once praised for their durability, strength, and low costs, are now at the centre of growing environmental concerns due to their contribution to pollution and waste. As global demand for plastics continues to rise, alternative materials and product designs are needed to comply with circular economy principles. This dissertation explores how product development can contribute to this transition by studying bio-based plastics and their use in durable products.

The world today relies heavily on plastics. The ease with which they can be altered to desired properties, combined with the possibility of mass production, has made them both versatile and inexpensive. It has allowed global production to double from 234 million tonnes in 2000 to 460 million tonnes in 2019 [1]. In 2019, plastic production accounted for about 9% of the global annual oil consumption and this is expected to rise to 20% in 2050 as demand for plastics continues to grow [2]. Plastics create large amounts of waste of which only 9% was recycled in 2019, with the majority ending up in incinerators, landfills or uncontrolled environments like dumpsites [1]. Inadequate disposal and wear and tear of plastic products contribute to environmental pollution through persistent macro- and microplastics, which takes decades or even centuries to degrade, severely impacting ecosystems [1].

The circular economy aims to shift away from the traditional linear model of "take, make, use, dispose" by creating a system where products and materials never become waste and nature is regenerated [3]. Through recovery strategies like reuse, repair, remanufacturing, and recycling, the value of materials is preserved, reducing the need for virgin resources and minimizing environmental impact. Bio-based plastics can offer a more circular alternative to conventional fossil-based plastics as they are produced, at least partially, from renewable biological feedstock [4, 5]. This creates a relatively short-term biogenic carbon cycle where carbon is stored in bio-based plastics by reusing, refurbishing, remanufacturing, or recycling products and released into the atmosphere through biodegradation or incineration at the end of a product's life where it can be taken up by plants again [6, 7].

Although bio-based plastics have been available on the market for several years and offer a potential as a sustainable alternative, their use remains limited. Currently, 0,5% of the world's plastic production is bio-based, however, their share is expected to grow with a significant higher rate than the overall growth of plastics [8]. Bio-based plastics are used in a wide range of products, but their main use is in textile fibres and packaging (see Figure 1.1).

Governments and companies have just begun to focus on the use of bio-based plastics in durable products. For example, the European Union published the 'Communication - EU policy framework on biobased, biodegradable and

compostable plastics', which states that priority should be given to bio-based plastic use in long-lived products over short-lived products [9]. However, there is currently no comprehensive EU legislation specifically regulating bio-based plastics, only two directives which focus specifically on single-use plastics and plastics bags that partially address bio-based plastics [10].

Much of the existing research on the potential uses of bio-based plastics also reflects this short-lived focus, often overlooking the potential and specific challenges of integrating bio-based plastics in durable, long-life products. A quick search on Scopus for articles from the past 10 years shows that there are more than twice as many results when searching for bio-based plastics in combination with applications with a (generally) short lifespan than with a long one (see Table 1.1). Yet, as shown in Figure 1.1, nearly half of bio-plastic applications are already durable products like consumer goods, textiles, and automotive parts, highlighting the lack of research in this area.

In product development, bio-based plastics remain relatively new and unfamiliar, especially in durable products. To support their broader and more responsible adoption, it is important to better understand the challenges and opportunities involved in developing durable products with bio-based plastics.

Table 1.1. Overview of search strings and number of results on Scopus in June 2025

Search string Article title, Abstract, Keywords	"biobased plastic*" OR "bio-based plastic*" OR "bioplastic*" OR "bio-plastic*" OR "biopolymer*" OR "bio-polymer*" OR "bio-based polymer*" OR "biobased polymer*"	
	AND	
	"single use" OR "short-lived" OR "packaging" OR "dispos*" OR "agriculture" OR "horticulture"	"durable" OR "long-lived" OR "electrics" OR "electronics" OR "automotive" OR "consumer good*" OR "consumer product*" OR "textile"
Article and Review results 2015-2025	6.840	3.008

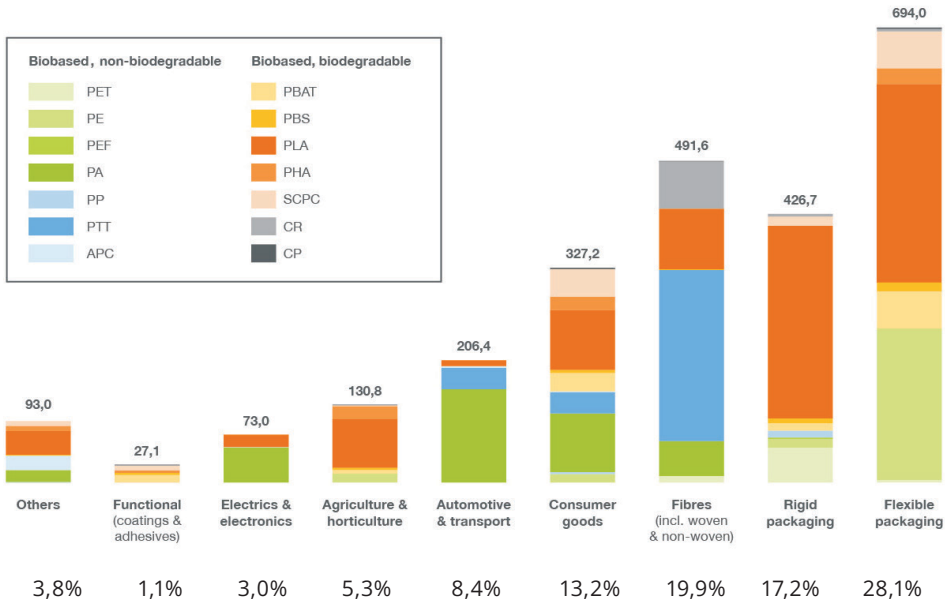


Figure 1.1. Global production capacities of bio-based plastics in 2024 by market segment in 1,000 tonnes, by European Bioplastics & nova-Institute [8]. Durable products like electronic, automotive parts, consumer goods, and textiles account for 44,5% of bio-based plastic use, while products with (generally) short lifespans such as packaging and agricultural products count for 50,6%.

1.1 BIO-BASED PLASTICS IN A CIRCULAR ECONOMY

The circular economy is often visualised with the butterfly diagram of the Ellen MacArthur Foundation which distinguishes between a technical cycle and a biological cycle. In the technical cycle, materials are ideally kept in the economy through loops like reuse or recycling, with the aim to use the smallest loop possible [3]. In the biological cycle, materials might gradually degrade through consecutive cycles, called cascades, losing quality until they eventually re-enter the biosphere through processes like biodegradation or incineration [3].

Since the distinction between biological and technological cycle does not always reflect the reality of industrial products containing bio-based plastics, Bakker and Balkenende have proposed the rainbow diagram (Figure 1.2). It is an adaption of the butterfly diagram and represents a range of recovery pathways with different focus points: product integrity focus (maintenance, reuse/redistribute, refurbish/remanufacture), material integrity focus (recycle), and carbon cycle focus (molecular decomposition) [11]. In the circular economy, the preferred cycles are those that preserve product and material integrity for as long as possible, and therefore molecular decomposition—which is only an option for bio-based materials—is the outer loop.

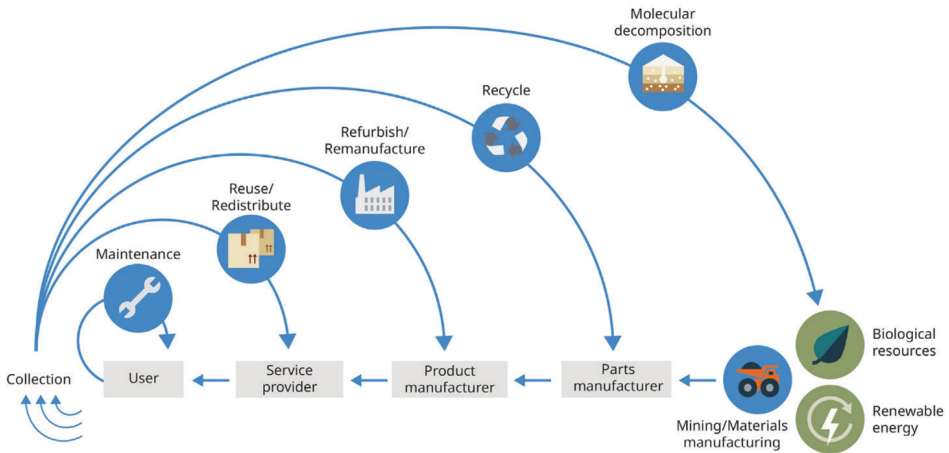


Figure 1.2. Rainbow diagram giving an overview of available recovery pathways for products and materials [11]

Besides considering the potential recovery pathways of bio-based plastics, it is also important to assess the origin of their feedstock, as this affects their alignment with the principles of the circular economy. Bio-based plastics can be made from various types of feedstock, such as plants and residual materials like agricultural waste. Each feedstock type has its own benefits and concerns. First generation feedstocks are edible crops. They contain a high amount of sugar which can be used for the production of plastics. However, using edible crops raises concerns about direct and indirect competition with food production and they require water and fertilisers to grow [12]. Second generation feedstock are non-edible biomass or by-products, avoiding direct competition with food resources but may depend on food production or compete for arable land [13]. Third generation feedstocks are algae, which do not require arable land or clean water [5, 14], however, their use in bio-based plastics is still in the early stages of development.

All these factors, from material sourcing consideration to differences in recovery pathways, highlight that developing durable circular products with bio-based plastics requires more than simply replacing regular fossil-based plastics with a bio-based alternative. For product developers, it can be difficult to navigate through all the different considerations and how to identify choices that are truly sustainable and responsible.

1.2 STATE OF THE ART AND KNOWLEDGE GAPS

While the material science of bio-based plastics is advancing—covering aspects such as synthesis of bio-based polymers, improved mechanical properties, and biodegradation behaviour [15, 16]—relatively little attention has been paid to the design perspective. Product developers play a central role in determining how and where materials are used, yet few studies have examined the practical challenges

they face when working with bio-based plastics in durable products. The lack of design-oriented studies means there is limited understanding of how these materials are perceived, selected, and integrated into actual product development processes.

Previous studies have begun to address this gap. Brockhaus et al. [17] investigated behavioural challenges faced by 32 product developers when considering replacing fossil-based plastics with bio-based alternatives. However, the product developers that were interviewed for this study were not yet involved in actually developing bio-based plastic products, limiting insight into practical implementation. Similarly, Cardon et al. [18] interviewed 13 stakeholders from across the bio-based plastic supply chain to explore opportunities and requirements for the adoption of these materials. Yet, only four of those interviewees were directly involved in product design and development, and the study is now over a decade old, which is significant given the rapid evolution of both the market and materials. Fletcher et al. [19] conducted four stakeholder engagement events to collect insights from multiple stakeholders across the bio-based plastics value chain, including manufacturers/producers, industry associations, retail, consumers, end-of-life. Although this more recent study provides useful insights on barriers encountered throughout the value chain, its primarily focus is on the production and adoption of bio-based plastics rather than product design.

As a result, there remains a lack of up-to-date, in-depth understanding of the current opportunities and barriers faced by product developers of durable products with bio-based plastics. For example, we know little about how these challenges manifest across the different stages of product development, or how design decisions are influenced by material characteristics, end-of-life options, and regulatory uncertainty.

Biodegradable plastics have gained increasing attention within the field of bio-based plastics for their potential to reduce plastic pollution, especially in situations where material recovery is difficult or unlikely [20, 21]. Most research on the applications of biodegradable plastics has mainly focused on short-lived applications such as agricultural applications (e.g., mulch films), medical products (e.g., sutures and drug delivery devices), and food packaging [22]. In contrast, the use of biodegradable plastics in durable products remains an underexplored area [23]. While durability is important for long-lasting products, certain use cases, such as products that wear down and release microplastics during use, raise the question whether biodegradable alternatives could offer a more sustainable solution. This is particularly relevant for ambiently biodegradable plastics that break down under ambient conditions. This highlights the need to better understand the practical implications and design opportunities for biodegradability in the context of durable circular products.

This dissertation addresses these knowledge gaps by taking a design-centred approach to the integration of bio-based plastics in durable products. Focussing on the context of industrial design in the EU, and in particular North-West Europe, it investigates how product developers currently engage with these materials, what challenges they encounter, and what opportunities they identify for supporting circularity through design.

1.3 RESEARCH QUESTIONS AND APPROACH

Developing products with bio-based plastics gives new opportunities and challenges. Guidance during the design and development process can help product developers make informed decisions, accelerating the adoption of bio-based plastics in durable applications and supporting the creating of more circular products. To contribute to this need, the central aim of this dissertation was:

To explore how bio-based plastics can be incorporated into the development of durable products designed for a circular economy.

To achieve this aim, multiple research questions were addressed. The first step was to gain an understanding of the current status of bio-based plastic use in durable products and what opportunities and barriers product developers perceived. The first research question was therefore:

RQ1: How are bio-based plastics perceived by actors throughout the value chain of durable consumers goods?

Insights were based on the outcomes of a workshop involving participants representing the entire value chain of a telecommunications company, ranging from product designers to those involved in end-of-life management. Most participants had little to no experience with bio-based plastics. This resulted in a list of perceived drivers and barriers and tensions between them. It also revealed several knowledge gaps regarding the use of bio-based plastics in durable products.

Based on the outcomes, the next study focused on gaining insight into the state of the art of bio-based plastic use in durable products and what product developers of these products actually encountered when using the plastics. It answered the following two questions:

RQ2: What is the current state of the art of bio-based plastic use in durable consumer products?

RQ3: What are the opportunities and barriers faced by product developers in the use of bio-based plastics for durable consumer products?

Two methods were used to assess current practices: a design analysis of existing bio-based plastic products, and interviews with people involved in the product development of these products. This resulted in opportunities and barriers linked to each process step of the Product Innovation Process model (formulating goals and strategies, product designing and development, marketing planning, production, and recovery).

Building on these insights, the next study explored whether and how biodegradability could help address microplastic pollution of durable products that wear. This brings new design challenges as it creates tension between durability and temporality, an aspect that has not yet been thoroughly explored. Therefore, the following research question was addressed:

RQ4: How can ambiently biodegradable plastics be applied in durable products that wear to reduce microplastic pollution in the environment?

A Research through Design (RtD) approach was used. Design explorations of three different products that wear (shoes, toothbrushes and marine rope) and resulting prototypes served as provocations for a discussion on the use of ambiently biodegradable plastics in durable applications, helping to uncover opportunities and constraints that were experienced through the design process. The findings regarding structural design are summarized in a design framework where the design principles 'insulation', 'substitution', and 'product lifetime extension', as well as implications for design are explained.

To help product developers develop durable products with bio-based plastics, the last study aimed to create guidance for them with considerations to take into account during product development. The research question was:

RQ5: 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?

With insights from the earlier conducted interviews (RQ3) and a scoping literature review, several relevant considerations across the product life cycle that influence the sustainable adoption of bio-based plastics were discussed. It concludes with guidance for product developers when they are developing durable products that align with circular economy principles.

1.4 OUTLINE

This dissertation is based on a series of submitted and published articles. The research questions described in the previous section are addressed through four studies, presented in Chapters 2 to 5. Chapter 6 provides an overall discussion and conclusion, reflecting on the main research question of this dissertation. In addition, this chapter outlines the contributions to science and practice. This dissertation concludes with recommendations for further research and concluding personal thoughts. An overview of the dissertation outline is shown in Table 1.2.

Table 1.2. Overview of the dissertation outline.

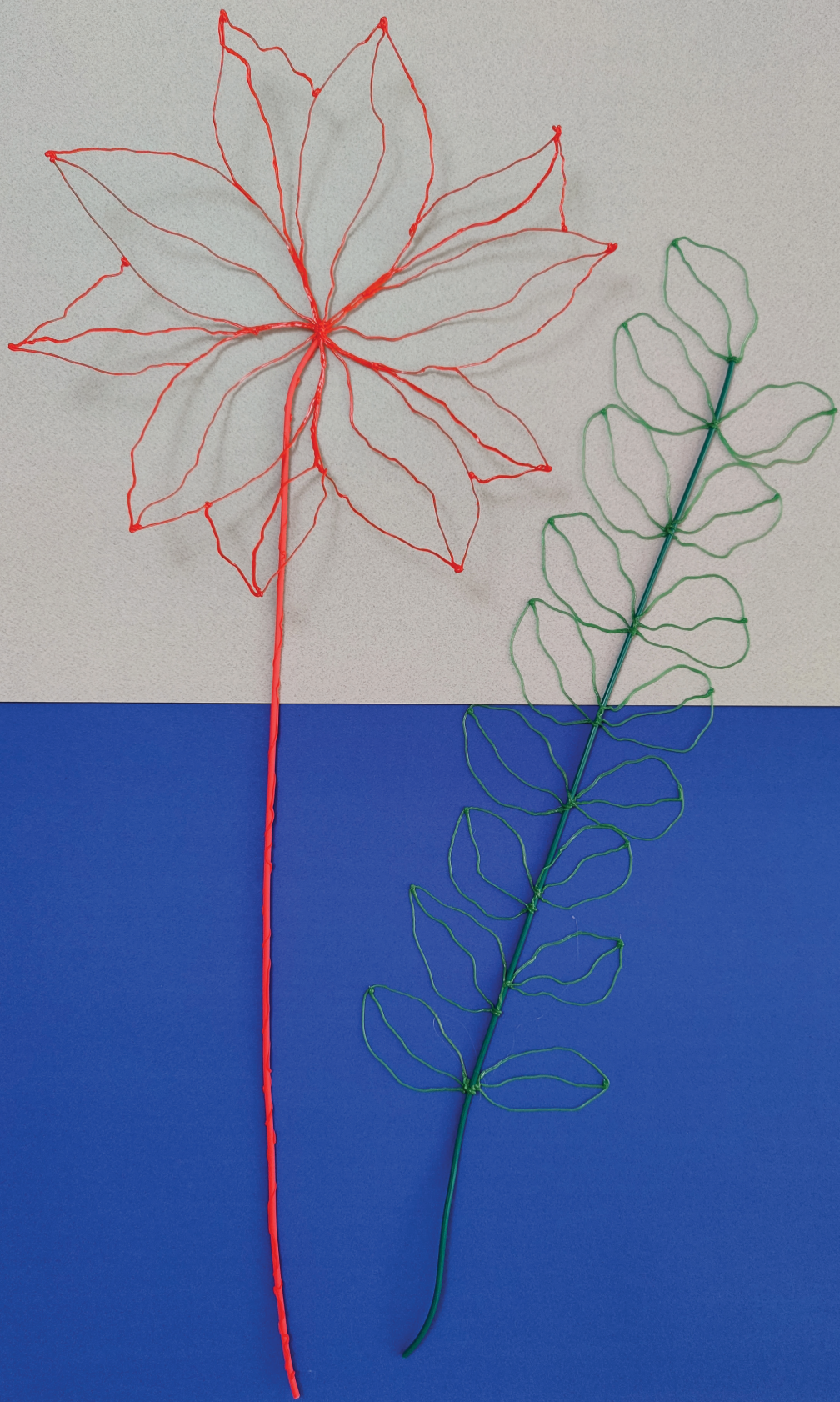
		Research question	
Chapter 1	Introduction		
Chapter 2	Drivers and Barriers for Bio-based Plastics in Durable Products	1	How are bio-based plastics perceived by actors throughout the value chain of durable consumers goods?
Chapter 3	Bio-based Plastics in Product Design: The State of the Art and Challenges to Overcome	2	What is the current state of the art of bio-based plastic use in durable consumer products?
		3	What are the opportunities and barriers faced by product developers in the use of bio-based plastics for durable consumer products?
Chapter 4	Products that Wear: Exploring How to Avoid Microplastic Pollution through the Design of Products with Ambiently Biodegradable Plastics	4	How can ambiently biodegradable plastics be applied in durable products that wear to reduce microplastic pollution in the environment?
Chapter 5	Designing with Bio-based Plastics: Practical Guidance for Circular Product Development	5	What key considerations do product developers face when using bio-bases plastics in the circular development of durable products, and how can they be supported in addressing them?
Chapter 6	Discussion and conclusion		

The next four chapters of this dissertation are based on articles published in scientific journals and presented at scientific conferences. Therefore, all chapters follow the format of the publication including introduction, body and conclusion. In order to make a consistent dissertation, the layout, section and figure numbers, and reference styles were adjusted. The content of the articles has not been changed and might result in some repetition throughout the dissertation.

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2

Drivers and Barriers for Bio-based Plastics in Durable Products

Contribution:

In the study presented in this chapter, I worked together with Linda Ritzen and Phil Brown to prepare and facilitate the workshop. I contributed to the development of the research design and shared responsibility for the data collection. As second author of the resulting conference paper, I contributed to the analysis, interpretation of the findings, and the writing of the paper.

This chapter was published as:

Ritzen, L., Bos, P., Brown, P., Balkenende, A.R., & Bakker, C.A. (2023) Drivers and barriers for bio-based plastics in durable products. *PLATE 2023: the 5th Conference on Product Lifetimes and the Environment*.

An additional overview of the employment fields of the participants of the study can be found in the supplementary information in table S1 [1].

ABSTRACT

Bio-based plastics are gaining attention as a sustainable, circular alternative to the current, petrochemical-based plastics. The main application of bio-based plastics is in single-use packaging with short lifetimes. Extending the application of bio-based plastics products towards durable consumer products requires the involvement of different value chain actors. An online interactive workshop, with 46 participants representing the entire value chain, produced a list of drivers for using bio-based plastics in durable consumer goods and barriers to overcome. The primary barriers to using bio-based plastics in durable products were related to their underdeveloped value chain and a need for more knowledge. The underdeveloped value chain was associated with high costs and no infrastructure for recovery at end-of-life, reducing potential environmental benefits. Participants indicated that they did not expect the value chain to mature without substantial government stimulations. Participants also noted a lack of knowledge among value chain actors as well as end-users. Value chain actors expressed that they need more clarity about what bio-based plastics are available and how they can be used in a sustainable way. While the market demand for sustainable alternatives is growing and bio-based plastics are a valuable marketing tool, users are poorly informed, and marketing should be thoughtful to avoid greenwashing.

2.1 INTRODUCTION

Plastics are vital for modern life, but their environmental impact and damage caused by plastic pollution necessitate a new approach. Plastic production consumes up to 8% of fossil fuels extracted annually [2], while it is estimated that 79% of all plastic ever produced has accumulated in landfills and the natural environment [3]. Bio-based plastics have the potential to enable circularity since they are based (at least in part) on biomass, rather than finite petrochemical resources [4]. The renewable nature of bio-based plastics enables circularity at the plastic production level. While only accounting for 1% of all plastics produced in 2022, the market for bio-based plastics is growing at over three times the rate of that of petrochemical-based plastics [5]. The Circular Economy Action Plan contains plans to stimulate the bio-based sector [6].

Bio-based plastics can be divided into drop-ins and dedicated bio-based plastics [7, 8]. Drop-in bio-based plastics are chemically identical to petrochemical-based plastics of the same name, such as polyethylene (PE). Dedicated bio-based plastics have no petrochemical-based equivalent. Biodegradable plastics are plastics that can be decomposed by living organisms and can be bio- or petrochemical-based. Not all bio-based plastics are biodegradable, although the two are often associated [2].

The main application of bio-based plastics is in single-use packaging with short lifetimes [5]. The application of plastics in single-use products will likely be limited by environmental legislation in the European Union [9] and other countries [10]. The application of bio-based plastics may then shift towards durable products. However, applying bio-based plastics in products with extended lifetimes requires the involvement of value chain actors unfamiliar with these materials.

This study aims to unveil how bio-based plastics are perceived by actors throughout the value chain for durable consumer goods: in this case, the telecommunication sector. An interactive workshop produced a list of drivers for using bio-based plastics and barriers to overcome in order to extend the lifetime of bio-based plastic products from packaging towards durable consumer goods.

2.2 METHODOLOGY

In October 2020, 46 participants representing the entire telecommunications value chain attended an online workshop. Participants were approached through the network of a Dutch telecommunications company and that of the authors. Prior to the workshop, 39 participants filled out a survey about their role in their company and their experience with bio-based plastics. Table 2.1 contains an overview of the participants. Survey participants covered the entire value chain of telecommunications products, in addition to the fields of legislation and research. 26 out of 39 respondents were employed in a sustainability-related role.

During the workshop, the participants were given a brief introduction to bio-based plastics, followed by an interactive assignment. Participants were asked to fill out an online collaborative whiteboard with drivers and barriers to using bio-based plastics in durable products. Participants could place green dots on entries to mark them as important.

After the workshop, all entries were anonymised, and those not phrased clearly were removed. The remaining entries were independently coded by two of the authors and grouped into drivers and barriers. These drivers and barriers were developed into themes that describe the participants' attitudes towards using bio-based plastics in their durable products. To determine the perceived importance of each driver or barrier, the number of post-its corresponding to them was combined with the number of green dots they received.

Table 2.1. Overview of participants' role. Participants could select multiple answers.

Role	Number of responses
Design and/or development	10
Legislation	4
Management	10
Research	5
Sales and/or customer support	8
Sustainability	26
Other	1

2.3 RESULTS

2.3.1 Prior knowledge of the participants

Figure 2.1 displays the outcomes of the pre-workshop survey. The majority of respondents rated their knowledge about bio-based plastics as low to very low. Most also had little to no experience working with bio-based plastics. 8% of respondents were already producing products containing bio-based plastics, and 77% of respondents considered it likely to very likely that they would do so in the near future.

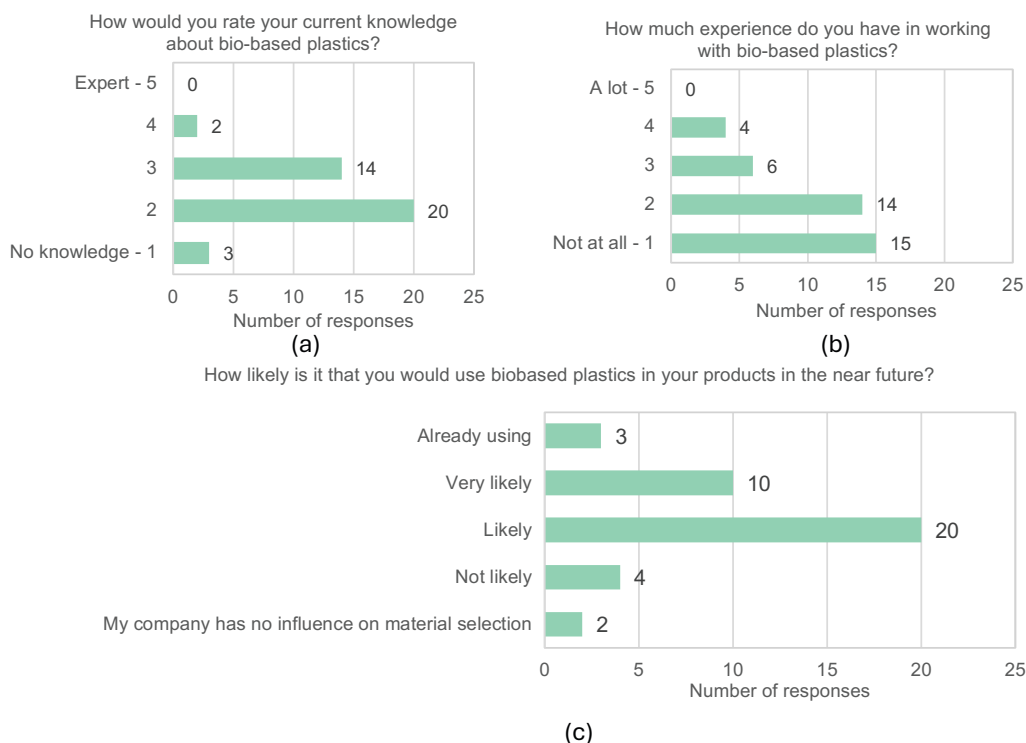


Figure 2.1. Outcomes of the pre-workshop survey about (a) prior knowledge of bio-based plastics, (b) prior experience with bio-based plastics, and (c) likeliness of using bio-based plastics in the near future.

2.3.2 Drivers and barriers to bio-based plastics usage

Drivers for bio-based plastics usage were categorised into the following seven themes: legislation, public perception, sustainability, design opportunities, sourcing, end-of-life, and collaboration. Below, the drivers for each theme are listed in order of perceived importance. It should be noted that the statements represent the participants' views and not necessarily the facts or the authors' views.

Driver theme 1: Legislation

- Existing and future regulations and sustainability targets could incentivise the use of bio-based plastics. For example, the European Green Deal, the Circular Economy Action plan, and CO2 emission targets.

Driver theme 2: Public perception

- Bio-based plastics can be used as a marketing tool to engage customers who are becoming increasingly environmentally contentious.
- Being an early adopter of bio-based plastics will reflect well on a company's image and establish them as a frontrunner.

- The interest in bio-based plastics in the corporate world is growing.
- Policymakers are driven by increased public awareness of environmental issues as well as business needs.

Driver theme 3: Sustainability

- Bio-based plastics can help companies to realise a circular business model.
- Bio-based plastics production can have a lower environmental impact than petrochemical-based plastics production.
- Bio-based plastics can be a sustainable solution for the long term due to their renewable resources.

Driver theme 4: Design opportunities

- Bio-based plastics can have new and unique properties that can be exploited in product design to add to performance and user value.
- Drop-in bio-based plastics can directly replace petrochemical-based counterparts, enabling a gradual transition.
- A new material creates the opportunity to experiment and develop new knowledge about its application.

Driver theme 5: Sourcing

- Bio-based plastics can be produced from a wide range of feedstocks, including waste, potentially resulting in a stable and local supply chain that is ultimately less dependent on fossil fuels.

Driver theme 6: End-of-Life

- Biodegradable (i.e. not per se bio-based) plastics can reduce waste and can be used to collect other compostable materials. For instance, biodegradable compost bags to collect home compost.
- Biodegradable plastics can provide a sustainable solution for products that wear or dissipate into the environment, such as tires or shoe soles.

Driver theme 7: Collaboration

- Being a new material, bio-based plastics allow for more interaction, knowledge sharing, and collaboration within value chains.
- Bio-based plastics can create new job opportunities.

Barriers to bio-based plastics usage could be categorised into the following seven themes: costs, lack of knowledge, sourcing, sustainability, end-of-life, an uncertain future and material properties. Below, the barriers for each theme are listed in order of perceived importance by the participants.

Barrier theme 1: Costs

- Bio-based plastics are more expensive than petrochemical-based plastics, increasing the price of a product.
- Users may not be able or willing to pay more.
- The entire value chain must change to accommodate bio-based plastics, which is expensive and time-consuming.

Barrier theme 2: Lack of knowledge

- Not all properties of new bio-based plastics are known. Bio-based plastics may have a lower technical performance than petrochemical-based plastics.
- Adding more variation in plastics adds complexity to proper disposal, making it confusing for end-users.
- It is risky to communicate bio-based with end-users because they do not have much knowledge about the concept, and the environmental benefits are still unclear.
- There are no clear guidelines on how to use bio-based plastics.
- Policy makers are not well informed about bio-based plastics.
- Bio-based plastics are not well known throughout the value chain. There is also insufficient information available.

Barrier theme 3: Sourcing

- Transitioning fully to bio-based plastics may not be possible without competing with food supply.
- The current volumes of available bio-based plastics are too low to cover demand and to enable recovery at end-of-life for dedicated bio-based plastics.
- Pollution from biomass may transfer into the plastic.

Barrier theme 4: Sustainability

- There are no standards for measuring and communicating the environmental impact of bio-based plastics and no policies regarding resource use, potentially leading to greenwashing.
- There is not enough clear information available about the environmental impact of bio-based plastics production and whether it is lower than petrochemical-based plastics.
- Marketing a product as more sustainable may cause end-users to adopt a less critical consumption attitude.
- Company image may suffer if bio-based plastics are derived from biomass that has damaging environmental effects.

Barrier theme 5: End-of-life

- Recovery of bio-based plastics at end-of-life is not yet guaranteed. Especially for dedicated bio-based plastics, production volumes are too small to facilitate reverse value chain infrastructure.
- The degradation levels of bio-based plastics compared to petrochemical-based plastics during recycling are unknown.
- Recyclability still needs to be guaranteed by product design.

Barrier theme 6: Uncertain future

- Certification of bio-based plastics can be complicated, taking years to develop.
- It is unclear how the market will develop, and governments are not taking an active role.
- There is a strong lobby of oil companies.
- Bio-based plastics are a rapidly developing field, which is difficult for companies.

Barrier theme 7: Material properties

- The aesthetics of bio-based plastics may be perceived as less desirable or of lower quality.
- Bio-based plastics properties may not meet material regulations such as fire safety or skin contact.
- Material composition and properties could vary depending on the source.

2.4 DISCUSSION

Figure 2.2 presents an overview of the driver and barrier themes and illustrates the tensions between them. The observations are broadly in-line with pre-existing research. There is a tension between the positive public perception of bio-based plastics and their high costs. Bio-based plastics are more expensive than regular petrochemical-based plastics, which is often seen as a barrier [11–13].

The public perception of bio-based plastics is positive, and consumers state that they would pay an increased price for a bio-based product [11], but not everyone follows through on their stated willingness to pay more for a bio-based products [12, 13]. This value-action gap is a common phenomenon for more sustainable products.

Despite their positive perception, the general public's knowledge about bio-based and biodegradable plastics is poorly developed [14]. Using bio-based plastics could therefore be risky, according to the participants. The use must be communicated clearly to the consumer in order to justify an increased cost. When bio-based plastics are applied in durable products, the bio-based aspect is typically mainly reflected in marketing [15]. However, the concept of bio-based plastics is complex, and the sustainability of the plastics is not entirely proven. This puts a company at risk of being accused of greenwashing.

The lack of public knowledge also extends to the recovery of bio-based plastics, combined with a lack of recovery infrastructure. Participants were concerned about proper disposal of bio-based or biodegradable products by end-users, and then by the reverse value chain. After use, drop-in bio-based plastics can easily integrate into existing recovery streams. However, these streams do not exist for novel, dedicated bio-based plastics, and there are no regulations or standards for their recovery at present [16]. Biodegradable plastics are not yet accepted in most industrial composting facilities [17, 18], and rarely fully disintegrate in home compost or nature [2]. This creates the risk of doing more harm than good when using bio-based or biodegradable plastics.

Value chain actors themselves also lack knowledge about bio-based plastics. This already became apparent in the pre-workshop survey. Moreover, biodegradable plastics were often discussed during the workshop as if biodegradability is a property of bio-based plastics. However, biodegradable plastics are not necessarily bio-based, further highlighting the lack of knowledge and confusion. Furthermore, participants were not well informed about alternatives to the plastics used in their products. While bio-based packaging is already readily available, incorporating bio-based plastics in durable products requires the development of new knowledge.

Participants were divided on whether the environmental impact of bio-based plastics would be higher or lower than that of petrochemical-based plastics. Bio-based plastics are perceived to be more sustainable by many of the workshop participants as well as the general public [19], but this is not yet confirmed by lifecycle assessment [20, 21]. Exploiting the sustainable image of bio-based plastics in marketing while the actual environmental impact remains uncertain can lead to greenwashing [22–24].

Most barriers and tensions appeared to originate in the immature value chain of bio-based plastics, which was considered a major barrier. During the workshop, this was labelled as an apparent causality problem, more commonly known as a chicken or egg problem. The immature value chain makes bio-based plastics expensive and poorly understood, resulting in unclear environmental benefits. The value chain cannot develop if bio-based plastics are not used more widely, but it is also a barrier to more widespread usage.

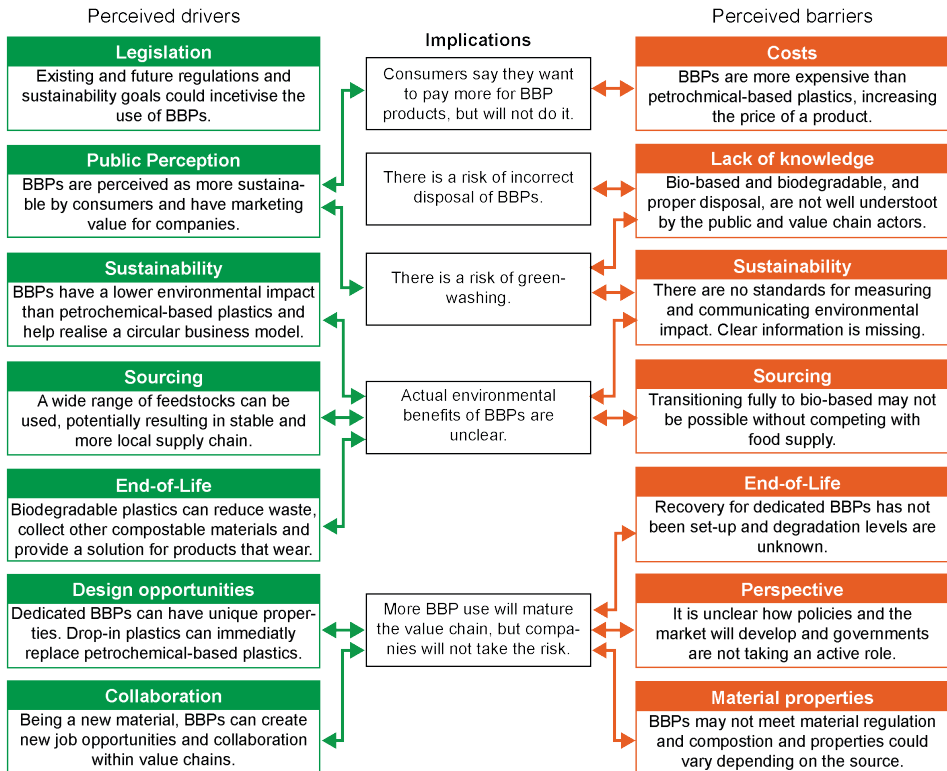


Figure 2.2. Overview of drivers and barriers for using bio-based plastics (BBP). Tensions between the drivers and barriers are highlighted in the middle column.

2.5 CONCLUSIONS

Although knowledge about and experience with bio-based plastics was low for most participants, they expected that bio-based plastics would be used in their durable products in the near future. Workshop participants reported legislation and public demand for more sustainable products as the main drivers for using bio-based plastics in durable products in the telecommunications sector. Some existing legislation already incentivises the use of bio-based plastics, but participants expected future legislation to further promote bio-based. Bio-based plastics can be valuable in marketing and design, but the lack of knowledge and confusing terminology surrounding them require careful consideration in order to avoid greenwashing.

The circularity and sustainability of bio-based plastics were seen as a driver as well as a barrier. Bio-based plastics are perceived to be more sustainable, but the environmental benefits of bio-based plastics production and upscaling are still debated. Many bio-based plastics cannot be recovered at end-of-life as of yet. Notably, sustainability was not considered as important of a driver as legislation and public perception.

If bio-based plastics are to find widespread usage in durable consumer products rather than single-use packaging, their value chain needs to grow, and information is still missing. The bio-based plastics value chain will not mature by itself but requires government stimulation. Furthermore, bio-based plastic packaging options are readily available, but applying bio-based plastics in durable products requires the generation of new knowledge. There need to be more resources about what bio-based plastics are available and how they can be used in durable products. The sustainability of bio-based plastics needs to be further studied: the environmental impact and the effects of land-use change due to upscaling are not clear at present. Recovery at end-of-life also needs to be guaranteed.

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3

Bio-based Plastics in Product Design: The State of the Art and Challenges to Overcome

Contribution:

In the study presented in this chapter, I conducted the design analysis and developed the interview study. I carried out all interviews, some in collaboration with Linda Ritzen, and led the overall data collection. Transcription was partly done by Linda Ritzen. A selection of the interviews was independently analysed by both of us. I also wrote the article based on the study. The other co-authors contributed to the study design and provided feedback through reviewing and editing the article.

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Information on the products of the design analysis and interview results can be retrieved from the supplementary materials [1].

ABSTRACT

Replacing fossil-based feedstock with renewable alternatives is a crucial step towards a circular economy. The bio-based plastics currently on the market are predominantly used in single-use applications, with remarkably limited uptake in durable products. This study explores the current state of the art of bio-based plastic use in durable consumer products and the opportunities and barriers encountered by product developers in adopting these materials. A design analysis of 60 durable products containing bio-based plastics, and 12 company interviews, identified the pursuit of sustainability goals and targets as the primary driver for adopting bio-based plastics, despite uncertainties regarding their reduced environmental impact. The lack of knowledge of bio-based plastics and their properties contributes to the slow adoption of these materials. Furthermore, the lack of recycling infrastructure, the limited availability of the plastics, and higher costs compared to fossil-based alternatives, are significant barriers to adoption. Product developers face significant challenges in designing with bio-based plastics, but opportunities exist; for example, for the use of dedicated bio-based plastics with unique properties. When designing with bio-based plastics, product developers must think beyond the physical product and consider sourcing and recovery, which are not typically part of the conventional product design process.

3.1 INTRODUCTION

The use of plastics has become a necessity in modern life, and the production of plastics made from fossil fuels continues to grow. In 2021, 90.2% of the 390.7 million tonnes of plastics produced were based on fossil feedstock [2]. It is evident today that using fossil raw materials is not sustainable. An alternative is bio-based plastic: plastics produced, at least partially, from renewable biological resources [3, 4]. In 2022, approximately 1% of all plastic processed was bio-based, and their share is growing [5]. Today's bio-based plastics on the market offer opportunities for both single use applications, such as packaging, and higher-value applications, including durable consumer products [4]. Durable is defined here as products that can be used repeatedly or continuously for a year or longer, under normal or average physical usage rates [6]. Today, bio-based plastics are mainly used in single-use applications [5, 7, 8]. Moreover, the existing literature on the potential uses of bio-based plastics primarily focuses on short-lived applications like packaging and does not explore the potential of bio-based plastics in durable products. Governments and companies have just begun to focus on the use of bio-based plastics in durable products. For example, the European Union published the Communication for an EU policy framework on biobased, biodegradable and compostable plastics, which states that priority should be given to its use in long-lived products over short-lived products [8]. However, there is currently no EU regulation in place on the use of bio-based plastics, only partial objectives in the Directive on single-use plastics and the Directive on plastic bags [9].

The use of bio-based plastics could facilitate the shift towards a sustainable and circular economy, as they potentially have a lower environmental impact [10, 11]. However, their actual environmental impact is in dispute, due to inconsistent Life Cycle Assessment (LCA) results. Poor data availability and the lack of a consistent methodology contribute to a substantial disparity in findings, making it challenging with the current constraints to draw well-founded and generalisable conclusions [12, 13]. Nevertheless, bio-based plastics have potential as they fit a circular economy well because the carbon absorbed during plant growth can be stored in the plastic by reusing and recycling bio-based plastic products. Eventually, the carbon is released back into the atmosphere through biodegradation or incineration and can be reabsorbed by plants [14, 15]. However, in order to ensure sustainability and circularity, feedstock sourcing and product and material recovery options need to be considered as well [14, 16–18]. A circular economy cannot be realised without better product design practice that incorporates all aspects of the product's life.

Limited research has been conducted to explore why designers are not using bio-based plastics on a larger scale in durable applications. Brockhaus et al. [19] examined the behavioural challenges that 32 designers faced when considering the replacement of fossil-based plastics with bio-based alternatives, but the designers in the study did not develop and introduce a bio-based product to the market themselves. Similarly, Cardon et al. [20] conducted interviews with 13 stakeholders in the bio-based plastic supply chain to explore the opportunities and requirements for implementing bio-based plastics in the future. However, this

study included only four people involved in the design and development process and is now 12 years old, which is a significant time for a quickly evolving market. Therefore, the challenges designers face in the current market when using these plastics are unknown. First, the aim of our study is to provide a recent overview of bio-based plastic use in durable consumer products by answering the following research question: 1. What is the current state of the art of bio-based plastic use in durable consumer products? Second, we aim to provide insight into what product developers encounter when using bio-based plastics by answering the following research question: 2. What are the opportunities and barriers faced by product developers in the use of bio-based plastics for durable consumer products? Answering these research questions provides new insights into the use of bio-based plastics in durable applications and what challenges need to be overcome to achieve more sustainable product designs.

We conducted a design analysis of 60 consumer products (e.g., toys, shoes and furniture) made entirely or partially of bio-based plastics. In the design analysis, products were evaluated against aspects related to product design like aesthetics, functionality, and sustainability. Next, 12 product developers involved in the creation of the analysed products were interviewed to understand the opportunities and barriers they experienced. Understanding these issues will help increase the sustainable utilisation of bio-based plastic, making the use of plastic more sustainable in the future.

The scope of this research was limited to product design and development of durable consumer products made of mass-produced, well-defined bio-based plastics. Natural polymers like paper and biocomposites, i.e., fossil-based polymers with natural fibres, are not considered in this paper. Also, it does not encompass aspects related to market analysis, recovery infrastructure, or the broader environmental impact of bio-based plastics. Conducting LCAs for individual products was not within the scope of this study. Sustainability assessments of products through existing LCAs were omitted due to current data limitations. Furthermore, the results represent the perception of product developers, which is not necessarily factually accurate, but serves to provide insights into their incentives and barriers when dealing with bio-based plastics. The products selected primarily originated from the European market, leading to a focus on the Western and Northern European context.

3.2 BACKGROUND

The subject matter of bio-based plastics can lead to confusion due to the presence of multiple definitions and the differentiation of various types of bio-based plastics. We will discuss this topic in more detail in Section 2.1, with an elaboration on the definitions used. This is followed by an explanation of the theoretical framework for this study in Section 2.2.

3.2.1 Bio-Based Plastics

Bio-based plastics are plastics produced, at least partially, from renewable biological resources [3, 4]. Fossil-based and bio-based both refer to the sourcing of the feedstock of the plastics (fossil or renewable). Biodegradability refers to the ability of a material to degrade by the activity of naturally occurring micro-organisms [21] and can be an end-of-life property of a plastic, but is not related to sourcing.

Bio-based plastics can be divided into two groups. The first group is called “drop-ins”, with an identical chemical structure as their fossil-based equivalent (e.g., bio-PE, bio-PET, and bio-PP), the second group is called “dedicated” plastics which have a new chemical structure (e.g., PLA, PHA, and some PA grades) [7, 22]. The definitions we use are shown in Table 3.1. Drop-in polymers can be either based on processed renewable biomass, usually by converting sugars to ethanol and subsequently ethene, or can be based on bio-naphtha, bio-methane, or vegetable oils [23]. In drop-in bio-based plastics, the renewable origin of the feedstock is directly traceable in products through the biogenic carbon atoms present. Sometimes, renewable biomass is mixed with fossil-based feedstock to make partially renewable polymers, which are sold as renewable through the so-called biomass balance approach. In biomass balance bio-based plastics, the renewable part of the feedstock is allocated to specific products through a certification system, but there is no direct physical link between the certified renewable feedstock and the final bio-based product [24]. Therefore, the amount of biogenic carbon atoms in the product does not necessarily correspond with the amount stated on the certificate of a given product.

Table 3.1. Overview of definitions related to bio-based plastics.

Bio-based plastic	Plastics produced, at least partially, from renewable biological resources [3, 4]
Biodegradable plastic	Plastics that can be degraded by naturally occurring micro-organisms such as bacteria, fungi, and algae [21]
Drop-in bio-based plastic	Bio-based plastics with identical chemical structure and properties as their fossil-based equivalent (e.g., bio-PE, bio-PET, and bio-PP) [7, 22]
Dedicated bio-based plastic	Bio-based plastics which have a new chemical structure and do not have an identical fossil-based counterpart (e.g., PLA, PHA, and some PA grades) [7, 22]

Resources for bio-based plastics are commonly divided into three categories: first, second, and third generation feedstocks. First generation feedstocks are edible crops, second generation feedstock are non-edible biomass or agricultural residues, and third generation feedstocks are based on algae [25, 26]. Most bio-based plastics are made from first or second generation feedstocks. The use of first generation feedstock has been criticised as it may compete directly or indirectly with food production [27] and needs large amounts of water and fertilisers [25]. Second generation feedstock has potential because unavoidable waste is used.

However, it can also have drawbacks as the availability depends on food production and the season [25]. New developments have led to third generation feedstocks, which have the advantage that they do not require arable land and water for their cultivation [26]. Third generation feedstocks are still at an early stage of development and the potential success of algal bio-based plastics in commercial use remains to be seen, as the costs and technical understanding of the extraction and conversion of algae for plastic production are uncertain and limited [28]. Each feedstock generation, therefore, seems to have its own advantages and disadvantages.

3.2.2 Product Innovation Process

We will now discuss the theoretical framework we used for the analysis of bio-based plastic product development. A widely used model in product development is the Product Innovation Process model by Roozenburg and Eekels [29]. This model visualises a common process in industry and entails all activities necessary to develop a new product for a market. It starts with an orientation phase where goals and strategies are formulated, then ideas are generated and selected. Different concepts and approaches to solving the identified problem or fulfil the defined need are developed. Once a promising concept is selected, the design is refined in the development phase. It involves making design choices, considering materials, and ensuring the design can be manufactured. Then, the product is manufactured and put on the market. After use by the consumer, the product, its parts and/or its materials should be recovered to ensure a circular economy. The model emphasises the iterative and non-linear nature of the design process, where product developers often cycle back and forth between stages as they refine and improve the design.

The use of the Product Innovation Process model provided a structured and recognised framework for structuring the interview results (see Figure 3.1).

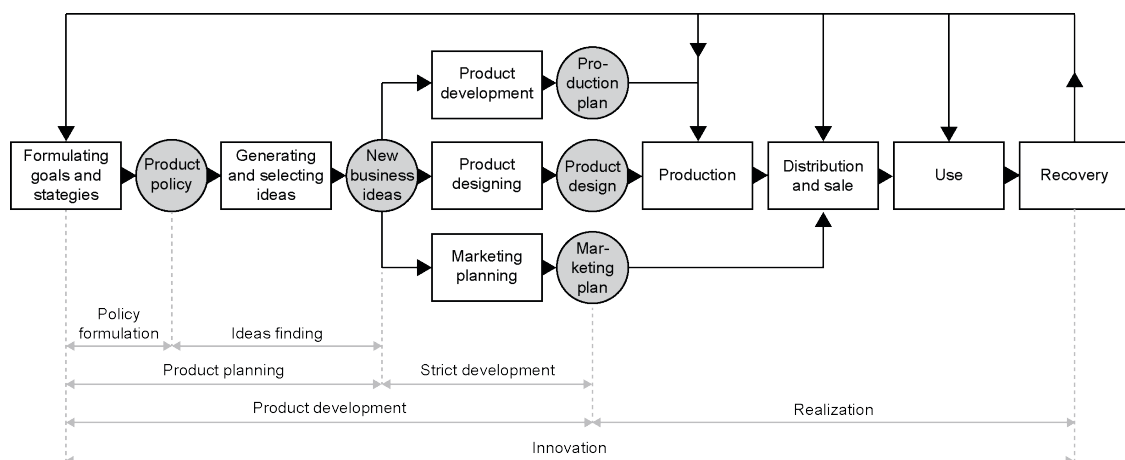


Figure 3.1. The Product Innovation Process model by Roozenburg and Eekels with the recovery step added [30]. The model shows all activities necessary to develop a new product for a market.

3.3 METHOD

Two methods were used to assess current practices: a design analysis of bio-based plastic products, and interviews with people involved in the product development of these products. Figure 3.2 shows the research process flow.

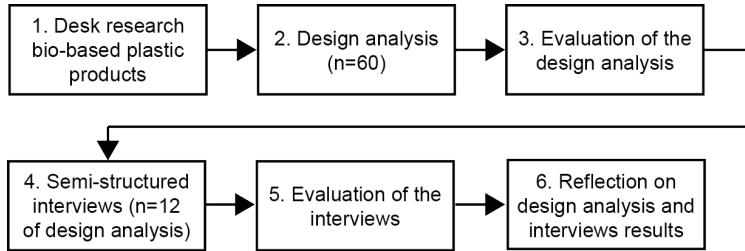


Figure 3.2. Research process flow chart showing principal steps.

3.3.1 Design Analysis

The design analysis followed the method as outlined in Bos et al. [31]. Desk research was conducted to identify durable consumer products made entirely or partially from bio-based plastics. This involved searching Google using keywords such as 'bio-based plastic', 'bio-based polymer', and 'bioplastic' along with 'product' or 'design'. Additionally, the online magazines Bioplastics Magazine [32] and Dezeen [33] and the website Bioplastics News [34] were used to find bio-based plastic products. The search was limited to products available on the market in the past 10 years to ensure the relevance and applicability of findings, considering the rapid developments in the field of bio-based plastics.

The study was based on observation and reflection by the authors, using information and pictures available on secondary sources (e.g., websites and magazine articles). If a brand produced a range of similar products, for example, different toys made from the same material, one representative product was included. Furthermore, representative products for similar products of different brands were selected. Products were only included if the type of bio-based plastic was given. The product information, including details about the bio-based plastic material, had to be available in English for them to be included. The results were categorised according to the 'Classification of Individual Consumption According to Purpose' (COICOP) [6]. This search resulted in a list of 60 products, which confirms that the proportion of bio-based plastics in durable products is small. Nevertheless, this search was not intended to be complete, but to be sufficiently broad to be able to investigate the current use and the opportunities and barriers as perceived by designers.

The products were analysed on the following aspects: Aesthetics, Functionality, Sustainability, and Marketing and Communication. These aspects were formulated based on the influence factors to the design process described by Ashby and Johnson and on the first author's five years of experience as an industrial designer in a commercial agency. According to Ashby and Johnson [35], the design context is created by five dominant inputs; industrial design, technology, economics, the environment and the market. We excluded the input 'economics'

due to the limited information available online about the product's viability beyond the selling price. The other inputs were considered while defining the evaluation aspects explained in Table 3.2. We reinterpreted 'industrial design' as 'aesthetics' as we were unable to judge the quality of the product's construction from the desk research, but we were able to comment on its more superficial characteristics (colour, visible texture, gloss, and shape).

The 'Aesthetics' aspect was evaluated based on the shape, colour, texture, and gloss of the product. The 'Functionality' aspect was assessed based on performance and durability compared to fossil-based equivalents, using product descriptions, material data sheets, and product architecture. The 'Sustainability' aspect was evaluated based on the feedstock generation and the end-of-life options mentioned in the available information, and to what extent recovery at end-of-life was arranged by the producer. Conducting LCAs for all products was beyond the scope of this study, but we did assess whether companies validated their sustainability claims through LCAs, and whether this information was publicly available. Finally, for the 'Marketing and communication' aspect, we evaluated whether bio-based was communicated on the product, in the product name, in the description, in the marketing campaign, or on the packaging. The collected data were organised in a table, and relevant additional information was recorded in brief notes.

Table 3.2. Evaluation aspects and how the products are analysed.

Aesthetics	The extent to which the aesthetics of the product—the shape, colour, texture, and gloss—appear to have been influenced by the use of bio-based plastics.
Functionality	The extent to which the performance (the ability to meet its function) and the durability (the ability to resist degradation and damage over time) of the product have, or have not, improved due to the use of bio-based plastics, according to the manufacturer.
Sustainability	The documented choice of feedstock and the extent to which the recovery has been considered in the design and business model. No Life Cycle Assessments (LCAs) were conducted for the products analysed in this study due to the unavailability of reliable information.
Marketing and Communication	The marketing approach emphasising the added value of bio-based plastics.

3.3.2 Interviews

Qualitative research through semi-structured interviews was conducted to uncover the opportunities and barriers to the application of bio-based plastics in durable consumer products and deepen the results of the design analysis. The companies behind the products of the design analysis were approached for an interview. In total, 46 companies were contacted via email and LinkedIn. Between March 2022 and November 2022, 12 companies agreed to an interview, 11 replied that they could not participate, and the other 23 did not respond after repeated requests. Contacting new companies was discontinued after 12 interviews as data saturation had been attained, meaning that additional interviews did not provide new insights.

The participating companies were of different sizes and had products in different product categories in their portfolio. Table 3.3 gives an overview of the interview sample, including the product category, the bio-based plastic used in the product, the professional position of the interviewee(s), and the company's size. To ensure anonymity, only the region in which the company operated according to the United Nations Geographic Regions [36] classification is shown. Applying the United Nations Geographic Regions, six of the companies are based in Western Europe, five in Northern Europe, and one in East Asia. This sample allowed different perspectives on the development of durable bio-based plastic products.

Table 3.3. Overview of the interview sample (I# = interview number, used for quotes in the result section).

I#	Interviewee(s) Position and Geographical Location <i>Western Europe (W-EU)</i> <i>Northern Europe (N-EU)</i> <i>East Asia (E-Asia)</i>	Company Size <i>Small (<10)</i> <i>Medium (10-100)</i> <i>Large (>100)</i>	Product Category	Bio-Based Plastic Type	
				<i>Dedicated (D)</i> <i>Traceable</i> <i>Drop-in (T)</i> <i>Biomass</i> <i>Balance (B)</i>	
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 PLA	(D) (D)
7	Production manager (N-EU)	small	Personal effects	PE	(T)
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 TPE	(T) (T)
11	Sustainability Leader (W-EU)	large	Household appliances and utensils	PP	(B)
12	Group leader * (W-EU)	large	Personal effects	PA	(D)

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

Two interviews were conducted in person at the respective company, and ten were conducted online. The interviews lasted approximately one hour per interview. An interview protocol was developed to structure the conversation. Before analysis, the interviews were recorded, transcribed, and anonymised with the interviewees' consent.

For each interview, the relevant text fragments were categorised according to the process steps of the Product Innovation Process model (see Figure 3.1). Table 3.4 shows the process steps and topics covered by the categories. Thereafter, similar content from different interviewees was clustered through open coding. In open coding, data are compared for similarities and differences forming groups of similar data [37]. This process resulted in opportunities and barriers linked to each process step in the Product Innovation Process model. As Corbin and Strauss [37] suggest, a researcher might unintentionally place data in an incorrect category, but through systematic comparisons, errors will eventually be identified, leading to the proper placement of data within the suitable category. In addition, five interviews were also analysed by the second author. Any discrepancies were discussed, revealing that there were only minor variations between the coding results. Therefore, it was decided that the remaining seven interviews did not need to be analysed again.

Table 3.4. Process steps of the Product Innovation Process model (see Figure 3.1) and the corresponding topics analysed in each step for the interview assessment.

Formulating goals and strategies	Company vision, company drivers, laws and regulation.
Product designing and development	Product aesthetics, material properties and quality, design and development process, material choice.
Marketing planning	Bio-based plastic market, marketing strategy, consumer perspective.
Production	Production and certification processes, material and production price, influence of plastic producer.
Recovery	Recovery options and infrastructure, consumer influence on recovery.

3.4 RESULTS

This chapter first presents the results of the design analysis in Section 3.4.1, then discusses the results of the semi-structured interviews in Section 3.4.2.

3.4.1 Results Design Analysis

During the design analysis, 60 products were identified. Table 3.5 gives an overview of the products, divided into product categories and the types of bio-based plastic used. The umbrella name of the plastic is used, because in many cases it was not clear with the commercially available data which grade and additives had been used. For elastomers, the class name TPE is used, as the type of elastomer was

not always stated. Bio-based plastics containing products covered a wide variety of product categories, from small products such as stationery items to furniture. Most of the products are in the categories 'Recreation: Toys and sports', 'Household appliances and utensils', and 'Clothing and Footwear'. In most products, only one type of bio-based plastic is used. Drop-in plastic PE and dedicated plastic PLA were the most commonly used.

Table 3.5. Number of partially or fully bio-based durable consumer products included in the design analysis, per product category and bio-based plastics used. Companies involved in the production of circled product categories were interviewed (see Table 3.3).

		Total per Category	Type of Bio-Based Plastic							
			CA	EVA	PA	PE	PHA	PLA	PP	TPE
Category	1. Clothing and Footwear	11		4	2					5
	2. Furniture	5				①	1	3		
	3. Household appliances and utensils	13			①	⑧		②	①	1
	4. Information and communication	6	1					③		2
	5. Personal effects	5	2		②	①				
	6. Recreation: Toys and sports	17			1	⑪		④		①
	7. Stationary and drawing materials	3					①	②		
Total		60	3	4	6	21	2	14	1	9

Table 3.6 summarises the results of the design analysis per product category. The analysis per product can be found in Appendix A. Since not all information was available online, some fields could not be filled out. Regarding the end-of-life option recycling, it was sometimes unclear whether the product could be recycled, although, in theory, the material was. These are not included in the table. This also applies to packaging in the Marketing and Communication aspect, since it was not always clear what the packaging of a product looked like, so it could not be determined whether bio-based was advertised on it.

Regarding the category 'Aesthetics', in almost all cases (57/60), the shape of the product was the same, or similar to, equivalent fossil-based products. In 24 products, the colours that were used were specifically chosen for the bio-based design. Figure 3.3 gives examples of bio-based products and their fossil-based equivalent. While the shapes were similar, the bio-based products often had a green or pastel colour. In addition, bio-based products more often had a matte finish whereas fossil-based products had a gloss finish.

Table 3.6. Design analysis results per product category (detailed results in Appendix A).

		Aesthetics				Functionality			
		Shape		Colour		Performance compared to fossil-based equivalent		Durability compared to fossil-based equivalent	
		Similar to fossil-based equivalent product	Specific design for bio-based material	Similar to fossil-based equivalent product	Specific colours for bio-based material	(Potentially) less	Similar	Better	(Potentially) less
Category	1	10	1	8	3		10	1	11
	2	5		3	2	1	4		1 4
	3	12	1	5	8	1	12		2 11
	4	6		4	2		5	1	1 5
	5	5		5			5		1 4
	6	17		9	8		15	2	1 16
	7	2	1	1	2		3		3
Total		57	3	36	24	2	54	4	6 54 0

* This may be more in reality as the packaging information was found for 43 of the 60 products.

Sustainability									Marketing and Communication				
Feedstock generation			Recovery mentioned by company						Bio-based communicated in/on:				
1st	2nd	3rd	Reuse	Repair	Recycle	Biodegrade	Incinerate	Recovery arrangements from company	Product	Product name	Description	Campaign	Packaging
6	4	1	6	3	2	2	3	5	2	5	11	8	3
4	1				1	4				3	5	3	1
8	5		5	1	13				2	10	13	6	11
3	3				3	5		2	4	4	6	3	4
2	3		1		1				1	1	5	2	1
11	6		6	1	13	3	4	4	1	10	17	6	15
3			3			3			3	3	3	2	1
38	21	1	20	4	33	17	7	11	13	35	60	29	35*



Figure 3.3. Many bio-based plastic products (top) have similar designs, but different colours than their fossil-based equivalents (bottom). From left to right: Vaude Skarvan Biobased Pants vs. Vaude Skarvan Pants, GastroMax Slotted turner BIO vs. GastroMax Slotted turner, Kartell Componibili Bio vs. Kartell Componibili, Dantoy BIO Bobsled vs. Dantoy Bobsled, Light my Fire Spork BIO vs. Light my Fire Spork.

Most products (54/60) appeared to have similar performance and durability compared to equivalent products made of fossil-based plastic. There were no bio-based products in the design analysis in which a bio-based plastic with better durability was used than the fossil-based plastic normally used for similar products. For six products, the durability appeared lower than fossil-based plastics typically used in equivalent products because a less durable plastic was used. For example, IKEA TALRIKA PLA-based tableware was recalled because these products could break at elevated temperatures, potentially causing burns [38]. Furthermore, products made of PHA could be less durable under some circumstances since PHA is biodegradable in natural environments such as sewage, soil, and seawater [39]. Four products boasted better performance than their fossil-based counterparts, according to the brand: the TPE in Scarpa's GEA skiing boots was lighter than fossil TPE [40], Fujitsu's M440 ECO mouse had a soft touch feeling due to the cellulose used [41], and Vaude's Skarvan Biobased Pants and Trail Spacer 28 backpack were lighter, with higher fibre strength and elasticity due to the bio-based PA used [42].

Regarding 'Sustainability', we assessed feedstock generation and end-of-life treatment. First and second generation feedstocks were primarily used, where the second generation feedstock was mainly castor oil or agricultural waste. One product used a small amount of third generation feedstock: Vivobarefoot used 5% algae-based plastic for their Ultra III Bloom shoe [43]. Ten companies

did not mention any end-of-life option. Among the companies that mentioned it, recycling was most frequently named as a recovery option (33/60). Biodegradation (17/60) was also mentioned, with certain companies explicitly referring to home or industrial composting. Eleven companies made arrangements to ensure end-of-life was executed as intended. These were typically take-back programs where consumers could return their product, and the company would repair or recycle it. One of the companies, On Running, sells fully recyclable shoes through a subscription service [44]. Ten companies cite a result of an LCA as evidence of their product's sustainability. Of these, six companies only disclosed the positive result without providing the full LCA report. Two other companies mentioned the positive LCA result of the material, but did not cover the entire product lifecycle, including lifespan and recovery. For two products, more detailed LCA information was shared. One of these companies used an alternative material for the calculations as no information was available for the actual material used. The other company indicated the items included in their LCA but did not provide exact values, so the LCA is not reproducible. In addition, only feedstock growth, production and transport were included in the LCA and not the consumer and recovery phase.

In 'Marketing and Communication', bio-based content was regularly used in the marketing campaign (28/60), as shown in the examples in Figure 3.4, and on the product's packaging (35/60). This included the use of various 'bio' certificates and labels. A reference to 'bio', 'green', or 'eco' was often in the name of the product (35/60), for example, 'BioCover', 'Eco Rigs', or 'Sacco goes green'.

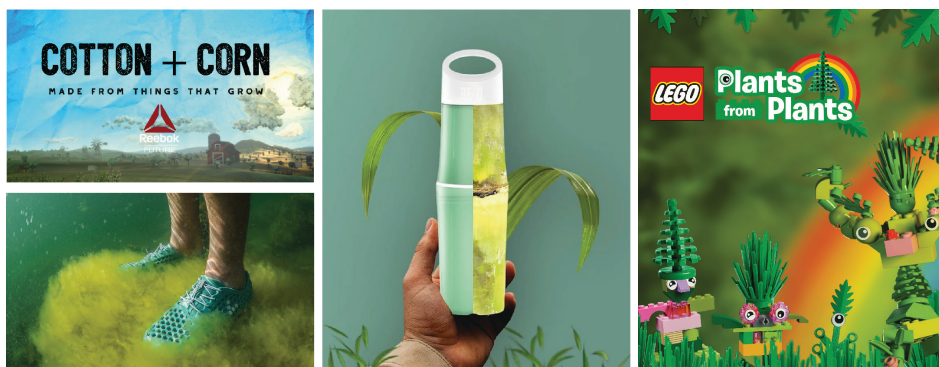


Figure 3.4. Bio-based content was regularly used in the marketing campaign of products, as shown in these examples (from left to right: Reebok, Vivobarefoot, Be O Lifestyle, LEGO).

The findings presented provide an overview of the current state of the art in commercially available bio-based plastic products. However, the results do not offer extensive insights into the underlying reasons for the observed patterns. Therefore, interviews were conducted to gain a more comprehensive understanding of the challenges and possibilities faced by product developers.

3.4.2. Results of Semi-Structured Interviews

Opportunities for and barriers to using bio-based plastics were derived from the interview data. Table 3.7 presents an overview of all opportunities and barriers, divided into product innovation phases according to the adapted Product Innovation Model (Figure 3.1). The 'n' is the number of interviewees who mentioned each opportunity or barrier, 'n'-values of 3 or higher are included in the table. In cases where notable results were mentioned by less interviewees, these were also included in the table. Detailed descriptions of all barriers and opportunities and relevant quotes can be found in the Supplementary Materials.

Table 3.7. Perceived opportunities and barriers found during semi-structured interviews with people involved in the development of bio-based plastic products, grouped per product innovation phase according to the adapted Product Innovation Model.

Formulating goals and strategies		
	Opportunities	n
1.1	Companies have a vision to be more sustainable and see bio-based plastics as a way to accomplish this.	10
1.2	Companies see using bio-based plastics as a start to transition away from fossil resources.	5
1.3	Companies see bio-based plastics as a means to sustainable sourcing in applications where recycled plastics are not permitted (e.g., food contact).	3
	Barriers	
1.4	Laws and regulations are lacking (e.g., regarding the differentiation between plastics or the end-of-life arrangements). Companies are waiting for rules, which slows development.	6
Product designing and development		
	Opportunities	n
2.1	Use the product's aesthetics (mainly colour) to communicate bio-based plastic use.	6
2.2	More and higher quality bio-based plastics are emerging on the market.	3
2.3	Drop-in plastics can be exchanged with fossil-based plastics without the need for additional research.	3
2.4	Dedicated bio-based plastics can offer unique advanced properties.	2
	Barriers	
2.5	Product developers question whether bio-based plastics are truly a sustainable material choice.	9
2.6	Many unknowns concerning new plastics ask for expensive and time-consuming R&D.	7
2.7	Biodegradable plastics are avoided in durable products due to the concern that they will decompose in the use phase.	7
2.8	The choice of available bio-based plastics is limited.	4

Marketing planning		
Opportunities		n
3.1	The market for bio-based plastics is growing.	9
3.2	Emphasising the sustainability of bio-based plastics in the marketing strategy.	5
Barriers		
3.3	Consumers lack understanding about bio-based plastics and their difference from fossil-based plastics.	10
3.4	Consumers are not willing to pay more for bio-based plastic products.	5
3.5	Marketing bio-based plastics as sustainable and safe can backfire and harm the company's reputation.	4
Production		
Opportunities		n
4.1	Biomass balance enables companies to continue using familiar production and certification processes while gradually shifting to bio-based materials.	3
Barriers		
4.2	Bio-based plastics are more expensive than fossil-based ones.	9
4.3	Only a few bio-based plastics producers dominate the market.	9
4.4	Using new plastics brings challenges to the production process.	4
Recovery		
Opportunities		n
5.1	Bio-based plastics have a lower carbon footprint compared to fossil-based plastics.	4
Barriers		
5.2	Consumers are uncertain about how to dispose of bio-based plastic products after use.	6
5.3	Infrastructure for recycling new types of plastics is lacking.	6

The following section will describe the main opportunities and barriers listed in Table 3.7. The pursuit of sustainability goals and targets was identified as the primary driver among the interviewed companies in adopting bio-based plastics (opportunity 1.1). One of the sustainability benefits mentioned was the lower carbon footprint compared to fossil-based plastics (opportunity 5.1). The growing market of bio-based plastics (opportunity 3.1), combined with consumer interest in sustainability, led them to invest in new (durable) products made with bio-based plastics. The interviewees also saw some major risks and barriers to the widespread implementation or upscaling of bio-based plastics for durable products. As many are related, we have combined them into four overarching topics: (1) gap in engineering and sustainability knowledge, (2) lack of end-of-life infrastructure and regulations, (3) high costs and limited availability, and (4) marketing value and challenges.

3.4.2.1 Gap in Engineering and Sustainability Knowledge

All interviewees mentioned a lack of information regarding bio-based plastics. Nine of twelve interviewees expressed doubts about the overall sustainability (barrier 2.5), for instance, regarding recycling of bio-based plastics: *"We have 60% bio-based PP and 40% wood fibre in those products [cutlery]. So when it comes to carbon footprint [...] I think it is a good thing. But [...] I would guess that it is not recyclable."* (I.7). Other issues discussed included the environmental impact of transportation, competition with food production, land use, and the fact that bio-based plastics do not solve the waste problem since they generate the same amount of waste as fossil-based plastics.

In addition, there seemed to be a lack of knowledge about the material properties and processing conditions of bio-based plastics, for example regarding biodegradability. Some companies, for instance, avoided using biodegradable plastics in durable products because they were concerned that the plastic might decompose during the use phase (barrier 2.7): *"Biodegradable you do not want either, because then the [household utensils we produce] will fall apart after 5 years"* (I.2). Uncertainties around dedicated bio-based plastics led to a strong preference among interviewees for drop-in plastics. Some companies emphasised the benefits of continuing to use known processes in the biomass balance approach (opportunity 4.1). Only two interviewees mentioned that dedicated bio-based plastics can offer unique, advanced properties that can be used in a product (opportunity 2.4). The design analysis also revealed that the unique properties of bio-based plastics are not being utilised to their full extent.

3.4.2.2 Lack of End-of-Life Infrastructure and Regulations

The interviewees noted a lack of recycling infrastructure for dedicated bio-based plastics (barrier 5.3). Therefore, some interviewees preferred drop-in plastics that can be recycled in existing recycling streams: *"We want [our household utensils] to remain recyclable. [...] So where possible, it should just be drop-in replacement for a PP, an ABS, and materials like that. And PLA as a replacement for ABS in electronics is not a sustainable option, in our opinion. Because that PLA can technically be recycled, but we currently know that it is not"* (I.11). Furthermore, other recovery pathways, such as industrial composting, are not universally available, making it less likely for companies to consider it as an end-of-life option when selling products internationally.

The interviewees also indicated that the lack of regulations on, for example, composting or recycling of dedicated bio-based plastics is a significant barrier to adopting bio-based plastics (barrier 1.4). Companies are waiting for rules and standards, which slows development. The drive for sustainable solutions that include bio-based plastics is currently mainly within industry.

3.4.2.3 High Costs and Limited Availability

A prevailing barrier to the development of bio-based plastic products was the dominance of a few bio-based plastic producers in the market (barrier 4.3). This results, for example, in limited availability of materials and higher prices compared

to fossil-based alternatives (barrier 4.2): *"You really have to pay more, count on a factor of two, sometimes even significantly higher"* (I.5). In addition to the fact that bio-based plastics are expensive, the companies report high research and development costs for changing to new materials, which also increase the product price (barrier 2.6). The interviewees expressed that consumers were reluctant to purchase bio-based plastic products due to these higher prices (barrier 3.4): *"You ask them: would you buy a bio-based product which costs 20% more than the normal one? Everybody says yes when they fill in the questionnaire, but then when you do the shopper study, no way"* (I.4).

Another consequence of the dominance of a few plastic producers is the fact that a limited number of different materials are manufactured. The design analysis confirmed that only a few bio-based plastic types, often from the same supplier, were used. During the interviews, four companies indicated that there is little choice in available bio-based plastics (barrier 2.8), making it challenging to select the suitable plastic for their application or to choose a particular feedstock generation. However, three interviewees indicated that they see more and higher quality materials emerging on the market (opportunity 2.2), presenting an opportunity for selection but requiring companies to be informed and updated to remain competitive.

3.4.2.4 Marketing Value and Challenges

According to the interviewees, consumers lack a general understanding of what bio-based plastics are (barrier 3.3). This may, for instance, lead to consumers being uncertain about how to properly dispose of bio-based plastic products after use (barrier 5.2): *"Many people still think that if you are dealing with bioplastic; it disappears when you throw it into nature"* (I.1).

It is, however, precisely this consumer belief in the benign nature and sustainability of bio-based plastics that has led many companies to emphasise sustainability in marketing strategies (opportunity 3.2). As we saw in the design analysis, companies often used colour to distinguish bio-based products from fossil-based ones and to justify the price difference to consumers (opportunity 2.1), although this distinction was primarily for marketing purposes rather than functionality. One interviewee shifted the focus of their marketing message from sustainability to safety, as they found that consumers were more receptive to the message that 100% bio-based toys were safer than fossil-based toys.

However, four interviewees also mentioned that marketing bio-based plastics as sustainable and safe can backfire and ultimately harm the company's reputation (barrier 3.5). It might be tempting for companies to seek or even cross the limits of what can be considered the 'truth', as the consumer market is easily persuaded to believe a sustainability claim: *"That is a bit the boundaries marketing always seek, because you do not want to do greenwashing, but you do want to have a sharp claim"* (I.11).

3.5 DISCUSSION

This discussion focuses on aspects that product developers can influence, such as material selection and knowledge acquisition; therefore, topics like material availability and costs have been excluded. Among the relevant topics from a product development perspective, we identified three main points of attention, namely (1) sustainability and circularity, (2) innovation, and (3) role of product development.

3.5.1 Sustainability and Circularity

One of the primary advantages of bio-based plastics is their sustainability potential. However, uncertainties surrounding their actual environmental impact were identified as an important barrier to their widespread adoption. The International Union of Pure and Applied Chemistry (IUPAC) states that bio-based plastics with the same properties compared to fossil-based ones cannot be considered better in terms of environmental impact unless a Life Cycle Assessment (LCA) indicates so [45]. LCA studies have so far given widely varying outcomes regarding the sustainability benefits of bio-based plastics. Factors that seem to have the most influence on the LCA outcome are the type of biomass used and its production location [46]. Reasons for the varying outcomes are the lack of a consistent methodology [12, 13] and poor data availability for chemical conversion processes [12]. In addition, a good result for the LCA of a material does not necessarily result in a better score for the LCA of a product, as factors such as longevity and recovery should also be included. Only a few companies in the design analysis claimed the completion of an LCA. However, as detailed data were not made publicly accessible, it was not possible to verify their results.

Despite the lack of LCA evidence, most companies consider bio-based plastics to be a sustainable alternative. Assumptions such as that bio-based plastics are inherently safe for humans and nature are propagated in marketing, spreading misconceptions amongst consumers. The literature confirms that consumers have an incorrect image of bio-based plastics. Kymäläinen et al. [47] conducted research with 44 Finnish consumers and found that 31 believed that bio-based toys such as LEGO were safer for children, despite being made of a drop-in bio-based plastic. In a recent literature review, Findrik and Meixner [48] confirm consumers' lack of knowledge of bio-based plastics, notably about their end-of-life characteristics (consumers assume that bio-based plastics are biodegradable) and environmental impact (consumers assume that bio-based plastics are sustainable). This may lead to misinterpretations among consumers regarding, for example, proper waste disposal [49]. Misleading marketing claims, intentional or unintentional, may also result in scepticism towards genuinely sustainable products, which can hinder their development [50]. The government can play a critical role by creating standards to counter misleading claims [51, 52] and providing more guidance to consumers through clear, uniform labelling [15, 53].

3.5.2 Innovation

In addition to the uncertainties surrounding the environmental impact of bio-based plastics, product developers are hampered by unknown material properties and processing conditions, and variations in plastic compounds. One possible explanation is that, until recently, the development of bio-based plastics has focused on packaging applications [54]. Therefore, material producers and suppliers may have primarily promoted and marketed the utilisation of bio-based plastics for packaging, paying less attention to their potential applications in durable products. On the other hand, the interviews did reveal that product developers saw the market for bio-based plastics growing, with more and higher quality bio-based plastics emerging on the market.

The design analysis and the interviews evidenced a lack of incentives to explore the unique properties of dedicated bio-based plastics. It raises questions about whether bio-based plastics are being used to their full potential. The interviews revealed risk aversion and a wait-and-see attitude among companies, who showed a preference for using drop-in plastics due to their familiarity and the ability to maintain existing processes, thus keeping research and development costs low. This creates a chicken-and-egg scenario for dedicated bio-based plastics where their market must grow before, for example, a recycling infrastructure can be set up, or prices can come down. Furthermore, companies are cautious with dedicated bio-based plastics because they are rapidly evolving, and there is a risk that a choice will soon become outdated. The lack of clear rules and uncertain prospects further strengthens their risk aversion, making it more likely that companies will choose to wait rather than take the risk of making a bad investment.

Several interviewed companies saw the biomass balance approach as a potential transition pathway towards an increased market share of bio-based plastics. However, implementing certification systems, such as the biomass balance approach, may create more confusion and distrust towards bio-based plastics because of the inability to track its sourcing and the risk of accidental or intentional misuse, like double counting of credits [55]. Taking a biomass balance approach allows companies to continue their current practices while claiming the benefits of bio-based content that might be present at an aggregated level but cannot be traced in their products. This approach also stops product developers getting on a learning curve regarding designing and producing with bio-based plastics.

3.5.3 Role of Product Development

All of this puts product developers in a difficult position. The lack of clarity on the sustainability of bio-based plastics makes it challenging to make informed choices. Lack of familiarity with the properties and processing conditions of bio-based plastics, misconceptions about their durability, and the lack of a recycling infrastructure for dedicated bio-based plastics, may make them hesitant to apply these materials in durable consumer products.

On the other hand, product developers can use their skills to create unique products that do justice to the properties of bio-based plastics. And they are in a potentially strategic position to steer consumers towards correct ways of disposing

and to educate them about the properties of bio-based plastics. Alternative ways, other than just using green and pastel colours, will have to be sought to communicate renewable content and educate the consumer.

If a company is serious about its ambitions to move away from fossil-based plastics, it should allow its research and product development departments time and leeway to explore and pilot a variety of bio-based plastics, and it should be reticent about adopting a mass-balance approach. However, we recognise that providing this space and time is costly and not without risk.

Regulation and standardisation could be of help here by, for example, (financially) stimulating sustainable material choices and making the choice for a bio-based plastic a less risky option. Additionally, scientists can help by further researching the added value of dedicated bio-based plastics for products and the circular economy. Future research should also explore how the unique properties of these plastics can be exploited in product design while considering the optimal circular economy pathways. Furthermore, it is evident that more research is required to determine the environmental impact of production, use, and end-of-life of bio-based plastics across the value chain to enable product developers to employ them in a sustainable manner. With the availability of such knowledge, product developers can design with bio-based plastics while considering the entire value chain (e.g., sourcing and end-of-life) and communicating this to the consumer.

Some limitations of this study should be noted. The desk review was limited by the information that was publicly available on websites and newsletters. Since the products were found through their producer's marketing channels, products could only be found if they mentioned the bio-based aspect in their marketing, which could have skewed the results of this research. As the search was conducted in English, the results were mainly from Western countries. Geographical conclusions can therefore not be drawn. A total of 12 companies were interviewed. In almost all cases, only one person per company was interviewed. This may not reflect all the vantage points within the company, but it does provide meaningful insights into the opportunities and barriers faced by individuals.

3.6 CONCLUSIONS

This research set out to explore the current state of the art of bio-based plastic use in durable consumer products and to identify the opportunities and barriers product developers perceived when designing with these plastics. The research involved two methods: a design analysis of 60 products to analyse the current use of bio-based plastics in durable applications and semi-structured interviews with employees from 12 companies involved in the development of the analysed products. The interviews gave insights into the barriers encountered when working with bio-based plastics and identified the opportunities perceived by the interviewees.

Product developers are seeking sustainable solutions for the ever-growing plastic use, including bio-based alternatives. The market of bio-based plastics in durable applications is still small and immature. There are a number of start-ups, and in large companies, bio-based plastics are generally used in a small proportion

of their product portfolio. Because the market is still in its early stages, we see a need for better education and knowledge dissemination for designers, companies, and consumers, as misconceptions and lack of information hinder the adoption and sustainability potential of bio-based plastics. Currently, it is not clear to what extent the use of bio-based plastics in durable products is genuinely sustainable or circular. Unfortunately, environmental impact assessment with LCA to substantiate claims is lacking transparent information. More research to resolve uncertainties surrounding the sustainability of bio-based plastics is required. The development of better standards and regulations can provide clarity and support the transition to a more sustainable and circular economy.

Although designing with bio-based plastics poses significant challenges for product developers, there are steps they can take to strive to create more sustainable product designs using bio-based plastics. We have the following recommendations based on this research:

- When using bio-based plastics, carbon is stored in the product. Aim for carbon sequestration by applying circular principles such as product life extension and recycling before incineration or biodegradation.
- Explore and pilot the use of drop-in and dedicated bio-based plastics and get on a learning curve. Dedicated bio-based plastics with unique properties (e.g., biodegradability) offer many opportunities for the future. The market is young and promising, with new bio-based plastics and applications being developed in increasing pace.
- Ensure proper consumer information, for instance on correct disposal, and prevent misleading claims about safety or sustainability.
- Be critical of LCAs, but do not let it be a reason for inaction. The available data do teach us that we need to carefully consider the biomass type and location, and the intended recovery of the product, and this is a valuable starting point.

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4

Products that Wear: Exploring How to Avoid Microplastic Pollution through the Design of Products with Ambiently Biodegradable Plastics

Contribution:

In the study presented in this chapter, I developed the overall study design, conducted the design explorations, and wrote the main body of the article. Linda Ritzen contributed by designing and conducting the analysis of currently available ambiently biodegradable plastics and writing the corresponding section of the paper. The other co-authors contributed to the study design and provided feedback through reviewing and editing the article.

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Information on currently available ambiently biodegradable plastics can be retrieved from the supplementary materials [1].

ABSTRACT

This study takes a Research through Design approach to explore how ambiently biodegradable (AB) plastics could be used in durable products that wear as strategy to reduce microplastic pollution, and how this affects the products' design. Through speculative design explorations, we developed a preliminary design framework for integrating AB plastics in sustainable product design. Our study addresses the tension between the need for durability of products and the temporality of biodegradable plastics that must break down under ambient conditions to prevent microplastic pollution. We explored the current limitations of AB plastics, including their mechanical properties and potential challenges in real-world conditions. Although the analysis is explorative, our findings indicate that AB plastics have the potential to serve as a viable solution for reducing microplastic pollution in applications where microplastic release is unavoidable. We also stress the importance of designing with circular design principles to ensure high-value recovery pathways are prioritized over biodegradation whenever possible. The study concludes by emphasizing the need for continued collaboration among product designers, material scientists, and biodegradation experts to further optimize the properties and applications of AB plastics, suggesting that practical testing and case studies will be key to advancing their use in sustainable product design.

4.1 INTRODUCTION

In recent years, microplastics (plastic particles smaller than 5 mm) have emerged as a significant environmental concern. Most plastics in use nowadays do not biodegrade naturally. When they end up in the environment, they slowly break down into small pieces. These pieces, often containing harmful chemical additives, end up in ecosystems and potentially affect soil properties [2, 3], organisms [4–7], and human health [8, 9]. The sources of microplastics are diverse, including intentional losses, such as microbeads in personal care products, and unintentional losses. These unintentional releases may occur during the use phase or maintenance of products, like wear and tear of synthetic textile and car tires [10], or after end-of-life due to spills during recycling [11] or slow degradation in the environment or in landfills [12].

Traditional solutions to this growing problem have focused on minimizing microplastic release (e.g., banning microbeads and reducing litter) and filtering microplastics from waste-water (e.g., filters on washing machines) [13, 14]. While these efforts offer effective solutions for some sources of microplastics, they do not address microplastic release from wear and tear of durable plastic products. As wear during use is inevitable (e.g., tires, shoe soles), this paper sets out to explore how biodegradable plastics might be used to address this problem.

Biodegradability is defined as the process of breakdown of a material by naturally occurring microorganisms such as bacteria, fungi, and algae [15]. Since plastics consist of very long polymer chains, microorganisms first excrete enzymes that can break down the chemical bonds in the polymers, reducing them to smaller intermediates [16]. These intermediates are then absorbed and digested by microorganisms into molecules such as water (H_2O), carbon dioxide (CO_2), and methane (CH_4) [17]. Currently, there are only a few types of polymers that are biodegradable in the natural environment, under ambient conditions (temperatures ranging from 20–32°C). Most biodegradable plastics require higher temperatures in an industrial process to successfully and rapidly break down into molecules. In this study we are only interested in the ambiently biodegradable plastics because we want to ensure that any microplastics that are released due to the wear of a product will degrade in the natural environment.

Ambiently biodegradable (AB) plastics were developed to break down in the natural environment in a relatively short time frame. There is no clear definition of AB plastic described in the literature, however, certification schemes from TÜV Austria for marine, fresh water and soil environments adhere to timelines of 90% biodegradation in 6 months, 56 days and 2 years, respectively [18]. At present, they are used in applications where these temporal properties are useful, for example in agricultural mulch films, where they break down on land, or in drug capsules, where they break down in the human body [10]. However, for many products designed to last, so-called durables, biodegradability is not a desirable property as a product should not perish before its intended life is over. If we want to use AB plastics to address the problem of microplastic release during wear of durables, we must address this tension between durability and temporality.

The aim of this study is to explore the application of AB plastics in durable products that wear, to reduce microplastic pollution in the environment, with the intention of developing a preliminary design framework that introduces a novel perspective on the use of AB plastics in design. Through speculative design explorations, we will address the tension between durability and temporality. The approaches can be expected to result in complicated trade-offs that need to be considered during design. The product's character, properties, experiential value, lifespan, and end-of-life will be affected. The intention of the design explorations presented in this study is to understand the likely changes and trade-offs that will occur and to develop a preliminary design framework which introduces a novel perspective on the use of AB plastics in design.

The line of thinking of using biodegradable materials for human purposes that can safely return to the environment is not new and exist in, for example, cradle-to-cradle design [19]. However, although extensive research has been conducted on sustainable materials, to the best of our knowledge no studies have specifically focussed on design implications of using biodegradable materials in the design of durable products to prevent microplastic pollution. While the Material Driven Design method of Karana et al. [20] also places material properties and possibilities at the centre of the design process, it typically starts with a known material, whereas this study takes a more speculative approach.

Biodegradation is a recovery pathway in the circular economy, and the approach taken in this study therefore complements existing circular design strategies such as design for recycling. However, currently available AB plastics are not optimised for the technical and functional requirements of mitigating microplastic pollution of durable products that wear. As such, this study adopts what DiSalvo [21] describes as *the tactic of projection*: using speculative prototypes to envision and provoke debate around alternative design futures. These prototypes are not final solutions, but rather conversation pieces that surface trade-offs, challenges, and opportunities of using AB plastics in durable products that wear.

This research followed two main approaches: speculative design explorations using AB plastics in products that wear and an analysis of currently available AB plastics. The explorative material analysis was used to reflect on the assumptions on AB plastics made during the design explorations. The approaches for the design explorations and material analysis are described in Section 4.2. Thereafter, the results of our design explorations are presented in Section 4.3, followed by reflections on the experiential aspects of using AB plastics and the material aspects of currently available AB plastics in Section 4.4. The insights gained in the design explorations and reflections are discussed in Section 4.5.

4.2 METHOD

4.2.1 Approach: speculative design explorations

This study follows a Research through Design (RtD) approach, where the development of a speculative prototype plays a central role in the knowledge-generation process [22]. As Stappers and Giaccardi put it: “For instance, it shows a hitherto non-existent combination of factors as a provocation for discussion, or it creates the possibility for people and products to engage in interactions that were not possible before, and these can come into existence—indeed, become observable—through the design.” In this study, the design explorations and resulting prototypes served as provocations for discussion, helping to surface opportunities and constraints that were experienced through the design process. The prototypes were created based on assumptions about material behaviour, product performance and degradation scenarios. These were not fully functional products with existing AB plastics, but rather conceptual explorations intended to reveal and discuss the underlying tensions which served as input for a preliminary design framework. As substitute for the AB plastic, we used 3D printed TPU, orange coloured spray paint and orange coloured rubber coating (Plasti Dip®).

In line with a practice-based design research approach, we allowed insights to emerge through the process of making and reflecting [23]. After the development of multiple prototypes per case, they were compared and synthesised thematically to identify recurring design strategies with accompanying challenges and implications, which informed the preliminary design framework. Additionally, the shoe prototypes were exhibited at the Dutch Design Week [24], where initial impressions of visitors were captured through informal feedback. Consumer interaction research, such as structured user studies or behavioural analysis, was not within the scope of this study. This research focused on exploring material possibilities, trade-offs, and design implications from a speculative and practice-based perspective.

4.2.2 Boundary conditions and assumptions

The design explorations were guided by several boundary conditions and assumptions. The first boundary condition was the circular economy – any product that is developed nowadays should, as a *conditio sine qua non*, fit in a circular economy. One of the core principles of the circular economy is that the value of products and the materials they are made of must be preserved by keeping them in the economic system, either by lengthening their life or looping them back in the system to be reused [25]. Plastics made of renewable, bio-based, feedstock do not contribute to global warming after degradation, as this is a carbon-neutral process (the carbon initially absorbed by the biomass is released back into nature on a relatively short timescale). Bio-based biodegradable plastics are designed to degrade through the action of micro-organisms, in the case of AB plastics even under ambient conditions. This suggests that ambiently biodegradable parts that are exposed to outdoor conditions may be less durable than their non-degradable equivalent. Therefore, the starting point for the design explorations was to limit

the use of AB plastics to the minimum, to allow as much of the durable (part of the) product as possible to cycle in high-value recovery loops, such as direct reuse, repair, and refurbishment.

A second boundary condition was the need for the AB plastics to be safe and non-toxic. When AB plastics biodegrade in the natural environment, they should in no way leave behind hazardous or toxic residues. Most plastics, including biodegradable plastics, contain a range of additives to enhance their properties. For the design explorations, we took as starting point that we would use only AB plastics without additives, as we had no data on the biodegradability and toxicity of additives. It followed, however, that without any additives, AB plastics would have poorer performance properties than conventional, non-biodegradable plastics. We therefore worked from the assumption that AB plastics have inferior mechanical properties (e.g., tensile strength, stiffness, fracture toughness) compared to commercially available polymers used in durables. We also assumed that the AB plastics would start to degrade as soon as they were exposed to the right ambient conditions. This is a logical scenario when the context of use also provides the right ambient conditions.

The final assumption is that AB plastics indeed mitigate microplastic pollution by biodegrading in the environment. We are aware that this claim should be made cautiously as biodegradation depends on specific environmental conditions like temperature and the presence of microorganisms. This study is therefore speculative, and more material research is needed before AB plastics can be used in these applications. Our scope is therefore mainly on the design implications.

4.2.3 Choice of cases

Three products in different use contexts were chosen for the design explorations: toothbrushes that wear in contact with teeth, shoe soles that wear on land, and marine rope that wears in water. These cases were selected to represent a diverse range of scenarios in which microplastics release is currently unavoidable. Each product has a different type of use and exposure to environmental factors, providing valuable insights into how AB plastics could be used in these applications. By selecting these three diverse cases, the study aims to uncover broader design principles that can be generalized to other applications involving wear-related microplastic emissions across diverse settings.

Toothbrushes represent close-contact use within the human body, posing challenges in terms of safety and hygiene. Toothbrushes are used daily which causes the bristles, usually made of polyamide (PA), to wear. The most visible wear is the bristles fraying and bending permanently. Fang et al. [26] showed that the bristles release microplastics during brushing, which can enter the digestive system or end up in sewage.

Shoe soles are subjected to variable environmental conditions such as moisture and contact materials like soil. Shoes are often (partially) made from synthetic materials, including plastics like thermoplastic polyurethane (TPU) for the soles, which wear during use. A German study by Fraunhofer UMSICHT estimated that shoe sole wear is the seventh biggest polluter of microplastics with 109 g per

capita per year [27]. A report from the Danish Environment Protection Agency estimated the total release from shoe soles to be roughly between 100 and 1000 t/year in Denmark alone, where it will end up in soil, sewage systems and agricultural soil from application of sewage sludge [28].

Marine ropes are exposed to prolonged immersion in saltwater, making them an interesting case for evaluating degradation in aquatic environments. Marine ropes and nets were formerly made from natural resources such as cotton, flax or hemp fibres, but today they are usually made from different types of plastics. Marine rope is known to be a major source of macro litter in the marine environment. However, the study of Napper et al. [29] additionally shows that large amounts of microplastic are formed during their use. The study shows that microplastics found in organisms like fish can be traced back to marine equipment such as ropes and nets [29]. Synthetic rope wear can occur internally (contact between yarns of the same rope) and externally (contact between the rope and another surface) [30]. Both types of abrasion occur during the use of marine ropes, mainly during hauling.

4.2.4 Analysis of currently available AB plastics

To reflect on the assumptions made during the design explorations, a scoping literature review as well as desk research into the state of the art of AB plastics was done. Properties of polymers from scientific publications on soil-, marine or freshwater biodegradation tests in 2023 and 2024 were included in order to provide insight into the most recent developments in the field. Furthermore, commercially available AB plastics were found through the certifying company TÜV Austria. Corresponding properties were retrieved from the technical datasheets of these materials.

The intention of this exploratory analysis was not to provide an exhaustive overview, but rather to understand how much the assumed properties of AB plastics on which we based the prototypes differed from currently available AB plastics, and from the non-biodegradable plastics that are normally used in toothbrushes, shoes and marine rope. This would help us understand what challenges might still be ahead for material development and design.

4.3 SPECULATIVE DESIGN EXPLORATIONS

The speculative design explorations into the use of AB plastics in products that wear resulted in various concepts for shoes, toothbrushes and maritime ropes. We divided the concepts into two design principles: insulation and substitution. The design principle of insulation will seek to preserve the durable character of the product and use AB plastic to 'insulate' the product from its environment. The idea here is that the AB plastic will wear away over time, leaving the non-biodegradable plastics undisturbed. The design principle of substitution seeks to find structural solutions to the use of AB plastics in durable applications, for instance by creating sacrificial parts of AB plastic in a durable plastic structure. By substituting some, or all, of the non-biodegradable plastic(s) of a durable product with AB plastics,

the product will fundamentally change character: its properties, structure, use, lifespan, experiential value, and end-of-life, will all change. In this section we will discuss the design principles of insulation and substitution, and a section on lifetime extension.

4.3.1 Design principle: Insulation

The design principle of insulation focusses on the durability of the product by using AB plastics to form an insulating layer that shields the product from its environment. The aim is to maximise the lifetime of the product while allowing the parts that wear down to do so safely. This approach allows the overall design and performance of the product to remain largely unchanged. This led to three different approaches, coating, buffering and wrapping, which we will now discuss.

4.3.1.1 Coating

Toothbrush bristles wear by friction between the bristles and the teeth. Both the tips and the sides of the bristles wear down [26]. The exact wear pattern will vary from person to person depending on brushing technique. For the design of the first concept toothbrush, we coated the entire outer surface of the bristles with AB plastics (Figure 4.1).

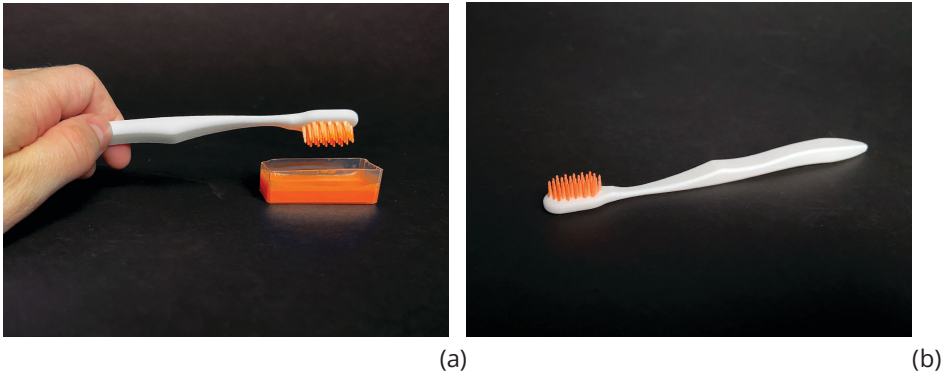


Figure 4.1. Toothbrush exploration #1 AB plastic coating (in orange) surrounding the bristles: (a) (re)coating the bristles and (b) coated toothbrush

Coating the surface of the bristles with AB plastics insulates the non-biodegradable plastic bristle hairs from direct contact with the use environment. The AB plastic will wear away, releasing biodegradable microplastics into the body and the sewage while doing minimal environmental harm and posing minimal risk to human health. A worn-out coating can be reapplied as shown in Figure 4.1. A challenge is adapting the design so that the coating can reach all areas of the bristles. Using thicker and fewer bristles ensures that the coating reaches properly around all the bristles, are less prone to permanent bending and will be easier to clean. Similar bristle designs with silicone bristles already exist on the market, demonstrating the feasibility and user acceptance.

A potential risk is that users may continue using the toothbrush after the coating has worn off, exposing them to microplastics from the underlying non-biodegradable material. To signal the need for a new coating, durable bristles with a different colour than the coating could be used, so that wear becomes visible through colour change, as is currently already standard practice with toothbrush bristles. Based on the assumption that AB plastics wear out quickly due to poorer performance properties, this probably will have to be done regularly. Furthermore, if the toothbrush is not rinsed properly after each use, microorganisms might remain on the bristles and biodegradation may occur even when the product is not in use, leading to faster breakdown of the AB plastic coating.

A similar insulation approach was chosen for the first concept shoe. The wear pattern of a sole depends on how the user moves the foot during walking. Due to abnormal pronation almost the entire bottom of a shoe sole can be subject to wear [31, 32] and hence the focus is on the entire sole. In this first shoe concept, the AB plastic coats the sole, and it is assumed that the coating will need to be reapplied regularly (Figure 4.2). Here too, not cleaning the shoe properly after having been exposed to soil and mud might hasten the biodegradation process. Similarly as with the toothbrush bristles, if the shoe is not recoated in time, this may lead to the release of microplastics from the underlying material into the environment.



Figure 4.2. Shoe exploration #1 AB plastic coating (in orange) surrounding the sole: (a) coating the shoe sole, (b) shoe with coating and (c) bottom of the shoe with coating

An advantage of an AB coating is that this approach can, theoretically, be applied to any shoe or toothbrush (or other durable products that wear) without fundamentally impacting the original design. For example, a coating could be applied to shoe soles temporarily before people enter a nature reserve, or the entire shoe could be coated to prevent contamination of an environment.

4.3.1.2 Buffering

A second approach to the principle of insulation is to create a thick AB plastic sacrificial buffer between the product and the environment. Figure 4.3 shows a concept where the bottom part of the sole is made of AB plastic and is attached to the shoe with studs, which allows manual replacement. A challenge is to ensure that as little material as possible has to be discarded when the wear part needs to be replaced.

An attempt to minimize the amount of buffer needed is shown in Figure 4.4. Here, the shoe is designed so that the non-biodegradable parts will not come into

contact with the ground. For this reason, the distance between the ground surface and the non-biodegradable middle part of the shoe is enlarged in the prototype. Furthermore, the sole extends upwards both at the front and back because this surface is likely to be in contact with the environment.

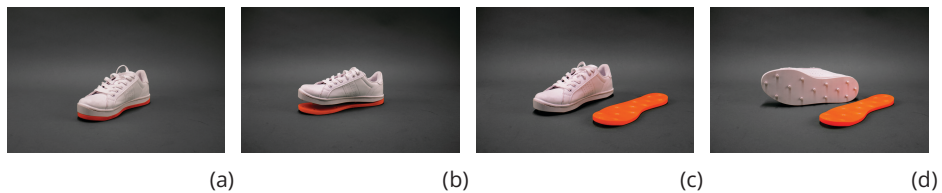


Figure 4.3. Shoe exploration #2 Bottom layer of the sole made of AB plastic (in orange): (a) AB plastic layer attached to shoe, (b) AB plastic layer partly removed, (c) AB plastic layer removed and (d) bottom of the shoe with attachment points



Figure 4.4. Shoe exploration #3 Sections of the sole made of AB plastic (in orange): (a) AB plastic sections attached to shoe, (b) AB plastic sections partly removed and (c) AB plastic sections removed

As different forces act on different areas of the sole, not every part of the sole will wear equally. The heel, for instance, could be made thicker to give the entire buffer an equally long lifespan. Since the exact wear pattern varies per user, this could also be individualised by, for example, offering different soles based on different types of pronation. As with a coating, the design of the product remains largely the same, even though a buffer is considerably thicker than a coating.

4.3.1.3 Wrapping

Marine rope has a different, and rather unpredictable, wear behaviour compared with toothbrushes and shoe soles. Not only the outside, but also the core can shed microplastics due to friction of the fibres during, for instance, anchoring, lifting equipment and fishing. This means that either these microplastics should not be able to leak into sea water through some form of containment, or they should be biodegradable, which means the entire rope should be biodegradable.

One idea is to have an AB plastic sleeve that wraps around the rope, protecting it and keeping the microplastics contained inside, like shown in Figure 4.5. However, given the assumed inferior mechanical properties of AB plastic, this is a potentially risky option. Sleeves are typically used to protect rope from rough surfaces and sharp edges. It follows that AB plastic sleeves will wear quickly

under such circumstances and a damaged sleeve will cause unwanted microplastic release. In this case, the use of AB plastic might be counterproductive, and unless the sleeves would be very regularly checked and replaced, this is unlikely to be a feasible option. Furthermore, this design might have limited effectiveness on microplastics shedding from the core of a rope, as the design of the rope itself is not changed.

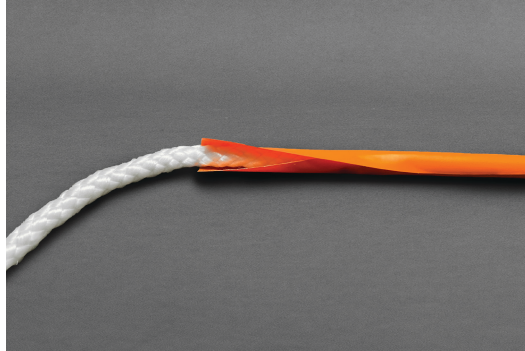


Figure 4.5. Rope exploration #1 AB plastic protective rope sleeve (in orange) around rope.

4.3.2 Design principle: Substitution

In the design principle of substitution, the material of (part of) the product that wears is replaced by an AB plastic to ensure the wear particles will break down. This affects the design and properties of the product or part. By limiting the AB plastic part only to the areas that wear, the durability of the rest of the product is maintained.

In our next design exploration, we focus on the entire rope being made of AB plastic. During use, water will penetrate to the inside of the rope. Thus, it is likely that the entire rope will already start to biodegrade during use. Combined with the assumed inferior mechanical properties of AB plastic, the result is a rope with a considerably shorter lifetime than conventional plastic ropes. It follows that the entire rope might need to be replaced regularly, resulting in the unwanted disposal of a lot of good material. Alternatively, the rope could change colour when worn allowing the weaker sections to be repaired, for instance with a technique called splicing. Finally, a thicker rope could be developed that would last longer but would also make it heavier and increase the environmental impact due to the use of more material. How much thicker and heavier this makes the rope and whether this is realistic depends on the exact material properties and context of use.

Contrary to shoe soles and toothbrushes, there is an ambiently (marine) biodegradable rope on the market: Senbis green rope. It is used for dolly rope, which is used in fisheries to protect the net from wear caused by contact with the seabed [33]. In real-life tests, the rope was found to lose its strength by 18% in 18 weeks [33]. Since dolly ropes should be replaced every 6 months, the lifespan is long enough for the application. This is an example where the choice for AB plastic is in line with the required lifespan of the product.

In the second toothbrush design exploration (Figure 4.6), a modular solution is explored, with only the bristles entirely made of AB plastic, to be replaced once sufficiently worn. Here, the AB bristles act as a sacrificial part in a durable structure. If a non-toxic and biodegradable pigment can be found, the bristle colour could fade over time, mimicking current bristles in toothbrushes. Creating a sacrificial part made of AB plastics requires a careful redesign of the bristle structure - the bristles are thicker to ensure effective brushing performance based on the lower strength of AB plastics, with sturdy bristle hairs that are less likely to deform. Since the toothbrush handle will not substantially wear during use, it can be reused and eventually recycled. Completely replacing a shoe sole by an AB plastic one would require a similar approach.

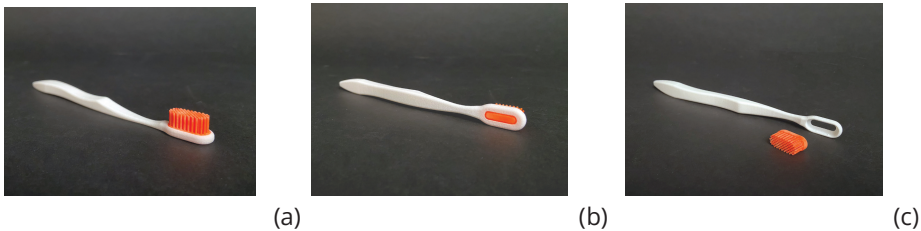


Figure 4.6. Toothbrush exploration #2 Replaceable bristles made of AB plastic (in orange) inspired by the Yaweco toothbrush [34]: (a) AB plastic bristles attached to toothbrush handle, (b) back of toothbrush with AB plastic bristles attached and (c) AB plastic bristles removed from toothbrush handle

4.3.3 Product lifetime extension

The concept of AB plastic parts wearing down implies that, in many cases, these worn parts will need replacement to extend the lifetime of the product. In the context of a circular economy this implies that the lifetime of a product is prolonged by operations such as maintenance and repair. The design explorations have already suggested several lifetime extension options, such as recoating toothbrush bristles or shoes and replacing AB plastic toothbrush bristles, buffers under shoe soles, or wraps around a marine rope. In addition to recoating and replacing AB plastic parts, we distinguish another potential lifetime extension strategy, which we refer to as replenishing.

Replenishing is the idea of rebuilding something that has been diminished. For example, a worn AB plastic shoe sole could be scanned to map where material is missing, after which the damage could be replenished with new material using Additive Manufacturing (see Figure 4.7). It is important that the new AB plastic can adhere to the damaged sole. If it does not adhere well, large pieces of AB plastic sole can come off, which take longer to biodegrade than microplastics. Replenishing can be especially interesting for parts that damage locally or for parts that exhibit a structure that wear down, like a shoe sole.

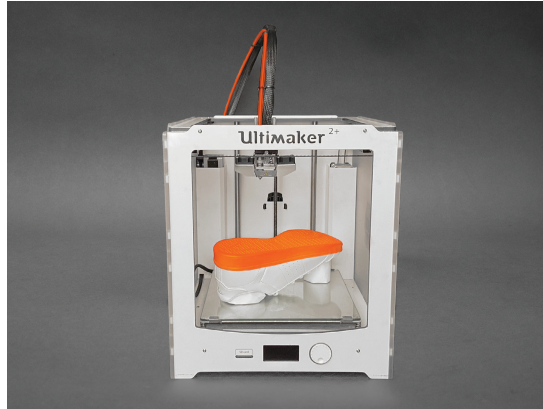


Figure 4.7. Shoe exploration #3 Replenishing AB plastic sole (in orange) with a 3D printer.

An important factor in extending the product's lifespan is cleaning of the AB plastic part. Since the AB plastics are designed to degrade under ambient conditions with exposure to microorganisms, it is important to minimise these conditions when the product is not in use. Properly cleaning the product after each use and storing it in a clean, dry environment will likely slow down the biodegradation process.

4.4 REFLECTION

4.4.1 Experiential aspects of using AB plastic

The integration of AB plastics into durable products changes not only functional properties and the design of the products but also the relationship of people with these products. We list here the main experiential aspects that emerged during the design explorations itself and from discussions about the designs with visitors of the 2023 Dutch Design Week [24], where the shoes were exhibited. Assuming these concepts would become reality, both negative and positive aspects might occur that designers and businesses need to deal with.

On the positive side, the concepts might open possibilities for totally new ways of perceiving and handling products. This could lead to new value propositions and service models (e.g., recoating as a service) that incorporate careful design with use cues and clear product information. If well-maintained and regularly replaced, some products (like shoes) may last much longer than usual as the AB plastic buffer prevents the wear of the durable plastic parts. This could not only extend the life of the main structure, but also create a long-term engagement with users. Furthermore, the replacement nature of the AB plastic component gives opportunities for modular design; for example, shoe soles with different profiles for different terrains, which potentially adds value to the user experience and sense of ownership and personalization.

People might be motivated to ‘do their bit’ to prevent microplastic pollution if it is made relatively straightforward and easy. If users understand that their maintenance and repair actions, such as replacing worn AB parts or keeping products clean, actively contribute to reducing microplastic pollution, they may feel more willing to adopt these routines. Additionally, if the replacement cycle is in line with normal habits there is a chance of quicker acceptance. For instance, in the case with the modular toothbrush people are already used to replacing their toothbrush regularly.

While AB plastics bring interesting possibilities, they also bring challenges. Products might be perceived as inferior; seeing a shoe sole wear faster than usual or having a rope break faster than currently expected might be difficult for users to accept and may lead to rejection. Also, the fact that a product looks or feels different may be a reason to reject it.

Likewise, the enhanced care and maintenance requirements could be a stumbling block for some users. Products made with AB plastics would likely require regular cleaning to prevent premature degradation. Furthermore, the AB plastic parts need regular maintenance like replacing or recoating. If the intention is that this is done by users, it may backfire, as people may simply buy a new product instead of replacing or recoating the AB plastic. And even if people are willing to replace or recoat, chances are that they might do it too late or too often, which defeats the purpose in different ways. If it is done too late, microplastic of the non-biodegradable plastic might be released and there is a risk that replacement might not be possible anymore because surfaces do not connect well anymore. If it is done too often it can have a negative environmental impact from increased material use.

In summary, while the introduction of AB plastics in product design presents several challenges related to user acceptance, maintenance, and perceived durability, it also opens opportunities for innovation in modular design, new service models, and a shift in user behaviour towards more sustainable product care and environmental responsibility.

4.4.2 Material aspects of currently available AB plastics

In our design explorations, we made several assumptions about AB plastics. To reflect on these assumptions, explore the feasibility of the proposed designs and uncover challenges for both design and material science, we conducted an exploratory material analysis of AB plastics currently available on the market and documented in the literature. This search was not intended to be exhaustive or definite, but rather to provide a fair impression of the mechanical properties of potentially interesting AB plastics, allowing for a preliminary comparison with the conventional plastics used in the design exploration products.

We compared the mechanical properties of AB plastics available on the market (#5-13 in Table 4.1) with the conventional plastics most often used in toothbrushes (polyamide (PA), polybutylene terephthalate (PBT), polypropylene (PP), polyethylene terephthalate (PET), silicone and polylactic acid (PLA)), shoes

(polyurethane (PU), thermoplastic polyurethane (TPU), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC)), and marine rope (polyethylene (PE), polyamide PA, polypropylene PP, ultra-high-molecular-weight polyethylene (UHWPE), aramid fibres and polyphenylene benzobisoxazole (PBO)) [35–37]. Commercially available AB plastics were found through the certifying company TÜV Austria. Corresponding properties were retrieved from the technical datasheets of these materials. TÜV Austria tests for soil biodegradability of at least 90% biodegradation at 20–25°C in 2 years, for freshwater biodegradability of at least 90% biodegradation at 20–25°C in 2 months and for marine biodegradability of at least 90% biodegradation at 28–32°C in 6 months [38].

Additionally, properties of polymers from scientific publications on soil-, marine or freshwater biodegradation tests in 2023 and 2024 were included in order to provide insight into the most recent scientific developments in the field (#1-4 in Table 4.1). Since biodegradation experiments in scientific literature use vastly different experimental designs (e.g., with respect to temperature and experiment duration), a threshold was set in order to be included in the results: the polymer needed to degrade at least 30% under ambient conditions within 180 days to be included.

Table 4.1. An overview of ambiently biodegradable (AB) plastics available on the market and described in literature. PBAT: polybutylene adipate terephthalate, PHBH: poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), PBS: polybutylene succinate, PBSA: polybutylene succinate-co-adipate, PHA: polyhydroxyalkanoate, PLA: polylactic acid, TPS: thermoplastic styrene.

#	Plastic type	Producer	Composition	Fresh-			Reference
				Soil	water	Marine	
1	TPS	n.a.	Thermoplastic starch based on cassava starch, glycerol, reinforced with sugarcane bagasse	X			[39]
2	TPS	n.a.	TPS with glycerol, guar gum, magnesium, and cabbage by-product	X			[40]
3	TPS	n.a.	TPS compounded with glycerol and calcium carbonate	X			[41]
4	PBSA	n.a.	Poly(butylene succinate-co-adipate) (PBSA) with wheat bran			X	[42]
5	PBAT/PLA	BASF	Ecovio: copolyester PBAT and PLA	X			[43]
6	Bio-PBS	Mitsubishi Chemical Corporation	FD grade: no details about composition reported	X			[44]
7	PBAT/TPS	Novamont	PBAT blended with TPS	X			[45]

Table 4.1. Continued

#	Plastic type	Producer	Composition	Fresh-			Reference
				Soil	water	Marine	
8	PHBH	Kaneka	Grade 151C, no details reported	X			[46]
9	PBAT	BASF	No details reported	X			[47]
10	Not reported	Golden compound	GC green 3092 MIF, no details reported	X			[48]
11	Not reported	Bio-FED	M-VERA, grades GP1045 and GP1012, no details reported	X			[49]
12	PHBH	Kaneka	Grade X131A, no details reported	X			[46]
13	PHA	NODAX	Danimer, grades 2192, 2194, 2513 and 2038	X		X	[50]

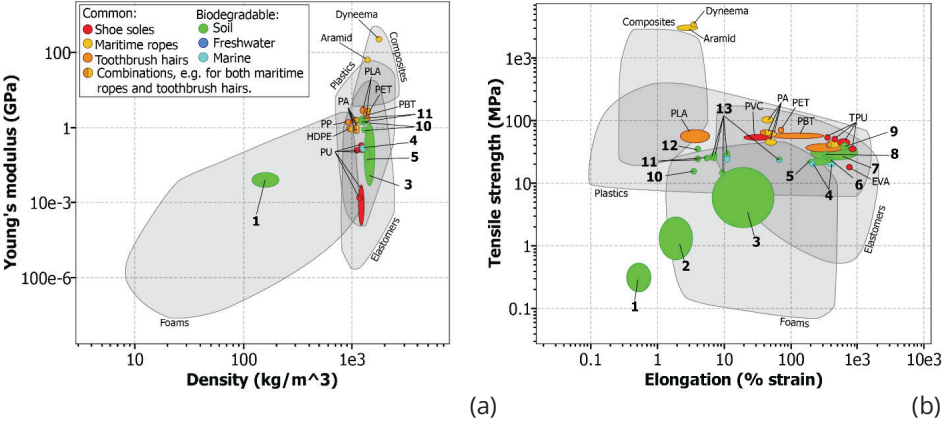


Figure 4.8. Ashby charts using Granta selector [51] showing the mechanical performance of ambiently biodegradable (AB) plastics compared to conventional plastics used in the three case studies: (a) density versus Young's modulus and (b) Elongation at break versus tensile strength.

Figure 4.8 displays Ashby charts of the mechanical properties of the AB plastics resulting from the material exploration. These charts provide an indication of the performance of biodegradable alternatives in the design explorations for selected properties and allows for a comparison with the properties of currently used materials. The properties in figure 4.8 were selected as they are representative of mechanical behaviour and the most reported in material data sheets and scientific literature. As figure 4.8b shows, the biodegradable alternatives typically have a lower tensile strength than the conventionally fossil fuel-based polymers for the design exploration products. Given that the scales are logarithmic, this difference is considerable: the tensile strength of the biodegradable polymers is less than half of that of most conventionally used polymers. The density of the biodegradable alternatives was also relatively high.

For the toothbrush hairs, water-biodegradable polymers had a relatively low stiffness and tensile strength compared to the conventionally used polymers.

Achieving a bristle with the current behaviour from a biodegradable polymer may currently not be possible. Since there was insufficient data on freshwater biodegradable polymers, we only used the results for marine biodegradable polymers for this analysis. For the shoe soles, one TPS type (number 3 in the Figure 4.8) and PBAT/PLA copolyester ecovio (number 5) showed a similar Young's modulus as conventionally used PU. However, the density was slightly higher, and the tensile strength and elongation at break were slightly lower. This implies that the shoe sole may be heavier and that the material may fail earlier during normal use. For the maritime ropes, marine-biodegradable polymers had a lower tensile strength, lower elongation at break and higher density than conventionally used materials. This may result in a significantly thicker and heavier rope as more material is needed to reach the same tensile strength and stiffness. This effect extends further as the rope needs to be thicker to carry its own increased weight.

This implies that straight-forward replacement of a plastic by an AB alternative can result in a product with very different mechanical behaviour. It also shows that for some applications, biodegradable plastics can currently not reach the required mechanical performance. Additives can be used to tailor the properties of a plastic and improve certain properties. However, these additives also need to be biodegradable in the targeted environments. The fate and effect of (biodegradable) additives in biodegradable plastics has not yet been studied outside of controlled lab environments [52]. Furthermore, blending of different polymers can enhance material properties of biodegradable plastics while maintaining biodegradability [53]. However, both blending and adding additives could make other recovery strategies like mechanical recycling more difficult [54].

In conclusion, current state of the art of AB plastics shows clearly that the mechanical properties are inferior to their non-biodegradable counterparts, which aligns with our initial assumption. This has implications for product design, as designers may need to compensate by, for example, using more material or accepting a shorter product lifespan. Additionally, the use of biodegradable additives that might improve mechanical properties is still an understudied area. More research in materials science is essential, particularly to better understand the biodegradation of AB plastics in open environments.

4.5 DISCUSSION

4.5.1 Use of AB plastics in products that wear to avoid microplastic pollution

Avoiding microplastic pollution by durable plastic products that wear is an understudied topic. Given the sheer number of products that wear in everyday use (e.g., shoes, tires, synthetic textiles, brake pads, brushes, brooms, ropes, products with wheels like trolley suitcases, toys, sports and recreation equipment, etc), it is crucial that more research is done into the design and development of these products and their materials. For some products, microplastics can be avoided by (re)introducing natural materials, but this will certainly not be possible

for all products. In many cases, the properties of natural materials will not be sufficient for the application, as they often have more variability in properties, mechanical performance, and consistency compared to engineered materials, making them less predictable and less suitable for mass production [55]. This study contributes to the understanding of how durable products can be designed to reduce microplastic pollution by offering a novel perspective on the integration of biodegradable plastics.

The speculative design explorations showed that the use of AB plastics as substitution or insulation is possible although this might come with considerable trade-offs. The inferior mechanical properties of AB plastics might to some extent be a given, but the overview of commercially available AB plastics shows that more research may be needed to push the boundaries. Material research could for instance explore how to better control the ageing and degradation behaviour of AB plastics, and how to use non-toxic and nature-compatible additives to improve mechanical properties without compromising overall biodegradability. Furthermore, as the biodegradation might already start during product use, it would help the design of products if the degradation process of AB plastics was better defined, such as when it starts, how fast it proceeds, and under what conditions, so that material characteristics are better understood.

The question remains whether the few commercially available AB plastics will fully biodegrade in real-world conditions. The certifying company TÜV Austria, for instance, certifies marine biodegradable plastics when they show 90% biodegradation within 180 days at 28 - 32°C [38]. It is questionable whether this standard provides a realistic picture, as the average ocean temperature is around 20°C, and there are obviously areas where the temperature is well below that [56]. The rate of degradation is probably much slower for certified marine biodegradable plastics in an ocean below 28°C [57]. Biodegradation in soil, seawater or fresh water will also vary greatly in, for example, microorganisms present, humidity, and oxygen level, affecting the degradation rate [17]. A change in testing conditions may be advisable in such instances, as well as more research into the health and environmental impact of not yet fully degraded AB plastics. In addition, there is also a risk of methane formation during the biodegradation process, which contributes to global warming [58]. This creates a trade-off between microplastic pollution and impact on climate change.

4.5.2 Design framework for using AB plastics in products that wear

Dealing with temporal aspects in the design of durable products is a new challenge. Designers need to reframe their thinking from creating maximum resistance to wear, to accepting relatively rapid wear of (parts of) the product. A good understanding of where and how a product wears and the degradation behaviour of AB plastics is necessary.

Integrating renewal services as part of the value proposition for some products can be positive for their circularity. However, temporality in durable products also creates a potential tension with some Circular Economy goals aimed at maximizing value retention and lowering environmental impact. Designers

may need to maximize the durable (long-life) part of the product and minimize the wearing (short lived) part and ensure both can be separated and correctly disposed of in their distinct recovery pathways. In addition to the design principles of substitution and insulation, it is therefore also important to consider recycling. A potential problem is that AB plastics could contaminate the recycling stream of durable plastics [59]. Furthermore, it is important to carefully consider the trade-offs between minimising microplastic pollution and reducing overall environmental impact. The use of AB plastic can require more material and its biodegradation can produce methane, which can lead to a larger impact on climate change compared to products made of conventional plastics. Clearly, introducing biodegradable materials in durable products introduces a variety of new tensions to the design process.

This study presented a first design exploration on the use of AB plastics in products that wear. Our findings regarding structural design can be summarized in Table 4.2, which also serves as a preliminary design framework.

Table 4.2. Preliminary design framework for structural design implications when using ambiently biodegradable (AB) plastics in products that wear

Design Principle: use of AB plastics in products that wear	Application in durable products	Possible implications and challenges for design
Insulation: Add an extra layer of AB plastic to surfaces of the product that wear, implying that the design of the product itself remains largely unaltered	Coating: a well-defined surface of the product that is subject to wear, is covered by a layer of biodegradable material. Most suited if temporary presence is sufficient, or if re-coating is no objection.	A challenge could be that the coating does not fully reach all wear-prone areas. Redesign the product to make the wear surfaces easily accessible to coat. The user/environment risks exposure to microplastics from the underlaying material when the coating is worn off. Explore options to make it visually clear when a coating needs to be replaced.
	Buffering: biodegradable relatively thick layer is applied that lasts longer than a coating but does not require an entire part of the product to have biodegradable properties.	Think about making the biodegradable part easily replaceable to ensure longer lifespan of durable parts. Due to uneven wear, possibly large amount of material needs to be discarded when the parts need replacement. Consider the wear pattern of the part when designing to minimise waste.
	Wrapping: an additional enclosure made of AB plastic surrounding a product or part.	A damaged wrap can release microplastics of the underlaying material. Think about making the biodegradable wrap easily replaceable to ensure longer lifespan of durable parts or match to lifetime of the product.
Substitution: Replace material of (part of) the product with AB plastic, which implies that the design of the product or part needs considerable adaptation	Full substitution: an entire product that is subject to wear is substituted by a biodegradable equivalent.	The AB plastic product will probably have a shorter lifetime. Consider designing in line with the required lifespan of the product.
	Partial substitution: the part of a product that wears is replaced by an AB plastic part.	Think about making the biodegradable part easily replaceable to ensure a long lifespan of durable parts.

Table 4.2. *Continued*

Design Principle: use of AB plastics in products that wear	Application in durable products	Possible implications and challenges for design
Product lifetime extension: Restorative actions on the AB plastic part to prolong the lifetime of the product	Recoating: reapplication of a new coating layer when the coating is worn out.	Incorrect recoating can pose risks of microplastics still being released from the underlaying material. Consider whether it is necessary to be able to remove an old coating and whether recoating is done by the user or an expert through a service.
	Replacing: replacing an AB plastic part when it is worn out. This can be done for both a substitution and an insulation part.	Replacing parts may be complicated for consumers. During designing, think about how an AB part can be replaced and if this is done by the user or an expert through a service.
	Replenishing: rebuilding a part when part of the AB plastic is worn out (e.g., with additive manufacturing). This can be done for both a substitution and an insulation part.	If the new material does not adhere properly to the damaged product there is a risk of large pieces of AB plastics coming off. When choosing the AB plastic, consider that the plastic should adhere to the original part during replenishing.

The framework focuses on structural design implications. In order to make these design principles work well, some additional aspects need to be considered. The products must be easily cleanable so that microorganisms that activate the biodegradation process are not retained. And besides adjustments in the structure of the designs, designing products with AB plastics requires dealing with multiple tensions related to user behaviour. Users need to adapt their normal use and care routines quite drastically, which may lead to resistance. Guiding them with careful design (i.e., colour change in wear parts, giving guidance on correct cleaning and disposal of AB parts, etc) and possibly offering new service models can help in the transition.

The study has several limitations that should be acknowledged. Many of the reflections presented are based on experiences and interpretations of the authors during the design explorations, and while they provide valuable insights in a Research through Design approach, they remain subjective. Impressions gathered from the visitors of the Dutch Design Week were informal and exploratory in nature, capturing initial reactions rather than in-depth consumer understanding. Future research could focus more systematically on consumer interaction with products containing AB plastics. Furthermore, the AB plastics analysed in the material analysis are relatively new and less developed than the well-established materials with multiple grades available in the database Granta Selection. Although the material

analysis was carried out as an exploration to see whether it might be possible (in the future) to design products that wear with AB plastics, there are limitations in comparing the mechanical properties of new and established materials. Additionally, biodegradation depends on environmental conditions such as temperature and presence of microorganisms and therefore more research is necessary to validate the effectiveness of using AB plastics to mitigate microplastic pollution.

The design framework proposed is preliminary and has not yet been tested in practical design contexts. Possible next steps toward realising the use of AB plastics in products that wear include extending the exploration to identify feasible cases and develop practical examples to test the properties of (future) AB plastics and refine the design framework. This is complicated as it requires close collaboration of designers with materials developers and biodegradation experts. Finally, the work involves several assumptions about material behaviour, user response, and product performance that were necessary at this speculative stage; these assumptions can be verified through additional interdisciplinary research.

4.6 CONCLUSION

Alarming news of microplastic pollution forces us to carefully and radically rethink the way we currently design and use plastic products. Non-biodegradable plastics, mainly praised for their durability, are increasingly seen as major contributors to microplastic pollution. This paper explored the use of ambiently biodegradable (AB) plastics in durable products as strategy to reduce microplastic pollution, with the intention of developing a preliminary design framework that introduces a novel perspective on the use of AB plastics in durable design. Through design explorations we addressed the tension between durability and temporality. We based our design exploration on the use of AB plastics in cases of inevitable microplastic release in the environment caused by wear inherent to the use phase of a product. Furthermore, we used circular design principles, implying that more valuable recovery pathways than biodegradation should be prioritised whenever possible.

Our design explorations showed the potential of AB plastics as an interesting solution to tackle microplastic pollution from products that wear. AB plastic used in durable products challenges the mindset for both designers and users to move away from the traditional focus on durability. This opens the door to creative product designs and new business ideas, like renewal and maintenance services that could fit well with circular economy principles. While our findings suggest that the use of AB plastics in durable products has potential, there are still challenges to overcome, particularly concerning their lower mechanical properties. This might result in the use of more plastic overall and therefore accepting a higher environmental impact to avoid non-biodegradable microplastic release. More research is needed, for example in optimizing the degradation behaviour and addressing their performance in real-life situations.

To realise the full potential of AB plastics in products that wear, collaboration between product designers, material scientists, and biodegradation experts is essential. Expanding this research with additional case studies and practical examples will be an important step to enable implementation of AB plastics in durable products.

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5

Designing with Bio-based Plastics: Guidance for Circular Product Development

Contribution:

In the study presented in this chapter, I was responsible for the study design, data analysis, and writing of the article. The other authors contributed to the study design and provided feedback through reviewing and editing the article.

This chapter is submitted and under review as:

Bos, P.; van Dam, S.; Balkenende, R.; Bakker, C. (under review) Designing with Bio-based Plastics: Practical Guidance for Circular Product Design. *She Ji*

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.

5.1 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 [1, 2]. Bio-based plastics (plastics derived partially or fully from renewable feedstocks) present an opportunity to reduce 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 regenerated [3]. By storing carbon during their use and recovery phase and releasing it into the atmosphere at end-of-life through biodegradation or incineration, bio-based plastics are part of a biogenic carbon cycle [4, 5]. However, their integration 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 [6], there is limited guidance to support product developers making informed and sustainable design choices. Addressing this gap 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 costs of bio-based plastics. These considerations can vary across stakeholders involved in product development (collectively referred to as product developers), including management at a more strategic level, to material scientists, mechanical engineers, product designers and the purchasing department that will source the final materials. The study aims to provide guidance to help product developers address the considerations that emerge throughout the product life cycle. 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?

The focus of the study is on the use of bio-based plastics in durable applications within the European Union. 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.

5.2 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. [7] illustrates the flows of biobased materials in a circular economy emphasizing different material recovery loops (Figure 5.1). 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 [8], 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 [7, 9]. 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 [7]. 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 [6, 7, 10]. In addition, energy released during incineration and anaerobic digestion can be seen as renewable energy.

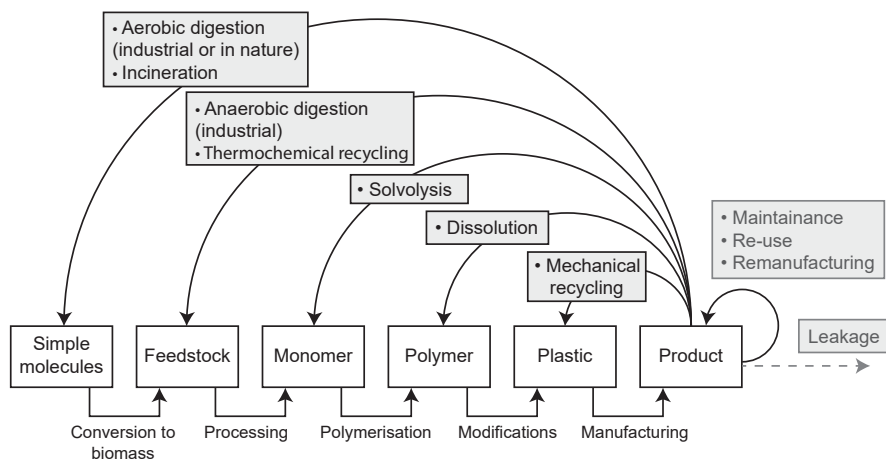


Figure 5.1. Framework for the circular economy of bio-based plastics incorporated into products by Ritzen et al.[7] The model shows the continuous material flows in a circular economy.

The life cycle of products made with bio-based plastics is shown in Figure 5.2. 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 5.1, 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 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.

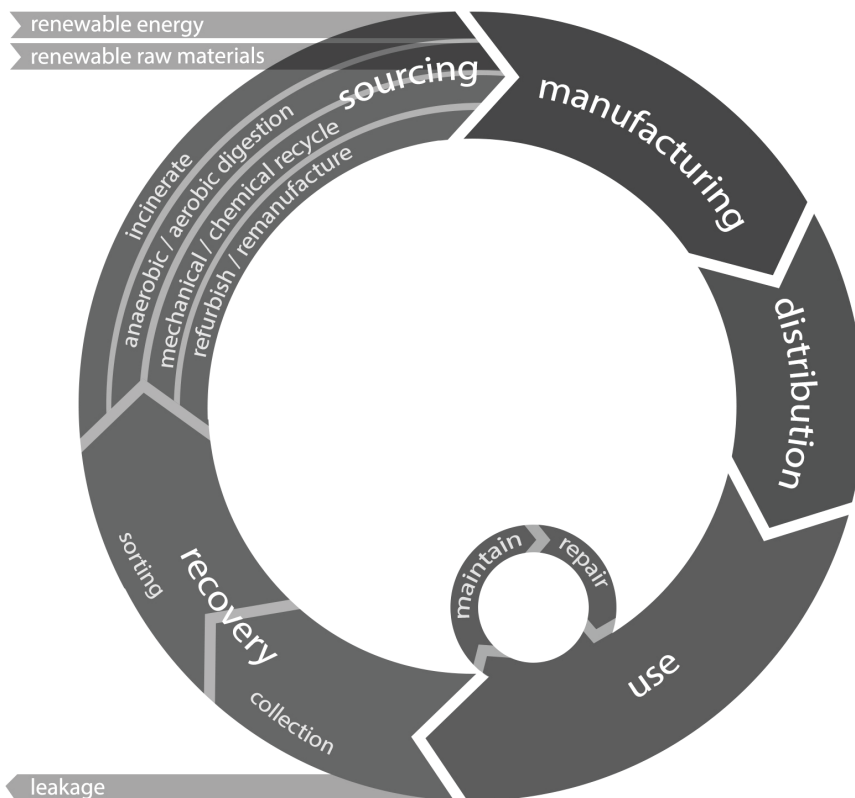


Figure 5.2. The product life cycle of bio-based plastic products

5.3 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.

5.3.1 Interviews

Between March and November 2022 semi-structured interviews with 12 product developers were conducted. Contacting new companies was discontinued after 12 interviews as data saturation was reached, meaning that additional interviews did not provide new insights. Table 5.1 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. Two interviews were conducted in person and ten were held online. Each interview lasted approximately one hour and followed a structured interview protocol. With the participants' consent, all interviews were recorded, transcribed, and anonymised prior to analysis.

The interview results were analysed using 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 [11]. 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.

5.3.2 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.

Table 5.1. Overview of the interview sample (I# = interview number, used for quotes in the result section).

I#	Interviewee(s) Position and Geographical Location <i>Western Europe (W-EU)</i> <i>Northern Europe (N-EU)</i> <i>East Asia (E-Asia)</i>	Company Size <i>Small (<10)</i> <i>Medium (10-100)</i> <i>Large (>100)</i>	Product Category	Bio-Based Plastic Type	
				<i>Dedicated (D)</i> <i>Traceable</i> <i>Drop-in (T)</i> <i>Biomass</i> <i>Balance (B)</i>	
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 PLA	(D) (D)
7	Production manager (N-EU)	small	Personal effects	PE	(T)
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 TPE	(T) (T)
11	Sustainability Leader (W-EU)	large	Household appliances and utensils	PP	(B)
12	Group leader * (W-EU)	large	Personal effects	PA	(D)

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

This search resulted in 593 journal papers and reviews. Our search was conducted in four main phases (see Figure 5.3). 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, 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 5.3) were rewritten into key considerations relevant to the development of products with bio-based plastics.

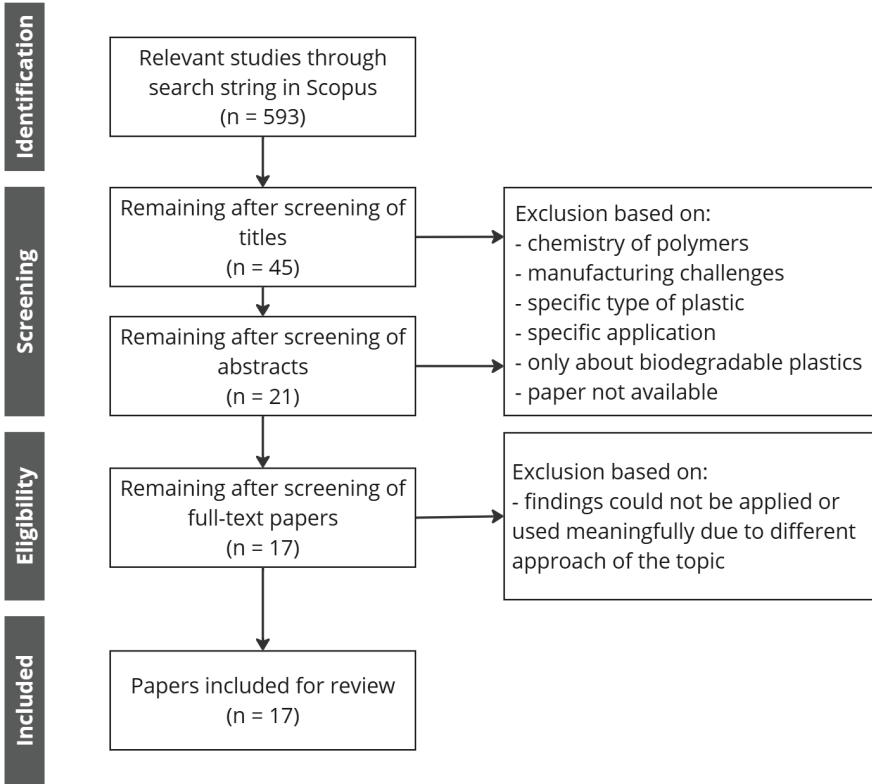


Figure 5.3. Graphical representation of the literature review search process

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.

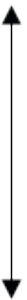
The biomass balance approach was not widely discussed in the initial literature review. However, it was included due to its growing significance to product developers when selecting bio-based plastics, as revealed in the interviews. Brief additional research was needed to better understand the state 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.

5.3.3 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 5.2. To further structure the analysis, the considerations were also assessed on macro, meso, and micro levels (Table 5.2). This distinction can enhance the focus and clarity by helping to organize the system [12]: 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.

Table 5.2. 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.	

5

5.4 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.

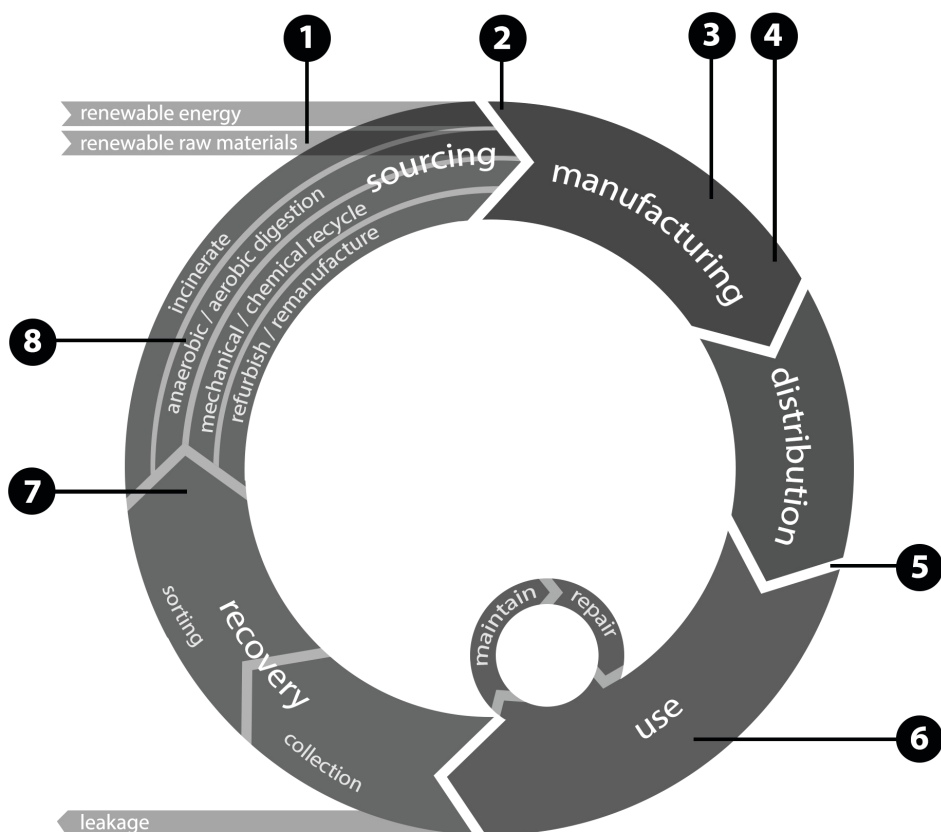
The scoping literature review identified 17 relevant papers discussing considerations when using bio-based plastics in product development. Table 5.3 presents the codes, the derived considerations, and the papers that addresses these topics.

Table 5.3 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 5.4). 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 5.4 and further explained in the text below.

Table 5.3. Literature on bio-based plastics and challenges when applying them to products.

Code		Consideration	Literature																
			Abrha et al., 2022 [13]	Bos et al., 2024 [14]	Brockhaus et al., 2016 [15]	Cardon et al., 2011 [16]	Di Bartolo et al., 2021 [17]	Fletcher et al., 2021 [18]	Goel et al., 2021 [19]	Jayakumar et al., 2023 [20]	Karan et al., 2019 [21]	Kawashima et al., 2019 [2]	Melchor-Martinez et al., 2022 [22]	Rahman & Bhoi, 2021 [23]	RameshKumar et al., 2020 [24]	Rosenboom et al., 2022 [1]	Schick et al., 2024 [25]	Storz & Verlop, 2013 [26]	Terzopoulou & Bikiaris, 2024 [27]
1	feedstock / sustainability / availability	Selecting the most sustainable bio-based plastic	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2	policy / leadership	Prioritizing leadership in bio-based plastic application versus focusing on compliance	x	x	x	x	x	x		x	x	x	x		x	x			x
3	novel / drop-in / properties	Choosing between easy replacement (drop-in plastics) and novel material properties (dedicated biobased plastics)	x	x		x	x	x			x	x	x		x			x	x
4	mass balance	Ensuring traceability of renewable content versus using the biomass balance approach		x				x											
5	costs / value / marketing	Weighing material costs against other values	x	x	x	x	x	x	x		x	x	x	x		x	x	x	x
6	consumer / education	Dealing with consumer perceptions	x	x	x	x		x	x	x		x	x	x		x			
7	recovery / performance	Balancing product functionality with designing for recovery strategies	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8	biodegradation	Considering biodegradability in relation to product durability	x	x			x	x	x	x	x	x	x	x	x	x	x		x



1	Selecting the most sustainable bio-based plastic
2	Prioritizing leadership in bio-based plastic application versus focusing on compliance
3	Choosing between easy replacement (drop-in plastics) and novel material properties (dedicated biobased 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 5.4. Key considerations when designing with bio-based plastics, mapped across the product life cycle.

Table 5.4. 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.	[1, 10, 16, 20, 26, 28]
2	Prioritizing 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.	[14, 15, 17, 20, 22]
3	Choosing between easy replacement (drop-in plastics) and novel material properties (dedicated plastics)	
	Product developers selecting bio-based plastics must choose between drop-in options, which are easy 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.	[14, 26, 29–33]
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.	[34–36]
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 environmental benefits, alignment with sustainability goals, and potential marketing advantages if ‘green’ marketing does not turn into greenwashing.	[10, 14, 15, 26]
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.	[10, 14, 18, 20, 37–40]

Table 5.4. *Continued*

#	Consideration	References
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.	[1, 7, 41]
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.	[1, 6, 42–46]

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.

5.4.1 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 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 [1, 10, 28], 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 [26, 28]. For example, the research of Ritzen et al. [28] 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 [28].

The use of bio-based feedstocks raises ethical concerns, particularly regarding their potential competition with food production [1, 16, 20, 26]. Most commercially available bio-based plastics currently rely on first-generation feedstocks, which are edible crops [47, 48]. Currently, only 0.02% of the world’s agricultural land is used for the production of bio-based plastics [22], however, this will increase as the share of bio-based plastics, which is currently 0,5% of the world’s plastic production, grows [49]. Although scientific data on the actual competition with food supply is lacking, ethical and ecological concerns (e.g., water use and deforestation)

are evident [1, 15]. 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 [1, 20]. 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 [50]. Third-generation feedstocks, such as algae, are promising but remain in the early stages of development and have limited availability [50]. The overall availability of bio-based plastics remains low due to limited production capacity and supply chain constraints [13, 18, 24]. Moreover, the currently limited choice in type of feedstock and origin often leaves product developers with few alternatives.

5.4.2 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 [20, 22], 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 [51]. However, existing directives are only focused on short-lived applications [52]. Compliance thus sets limited targets from a sustainability perspective.

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. 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 [14]. 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 [15].

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 [17]. 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 [53].

5.4.3 Consideration 3: Choosing between easy replacement (drop-in plastics) and novel material properties (dedicated biobased 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 easy replacement of fossil-based plastics with drop-in bio-based plastics or exploring novel material properties offered by dedicated bio-based plastics but require modifications to manufacturing processes.

Drop-in bio-based plastics are chemically identical to their fossil-based counterparts, allowing easy integration into existing production processes and recycling streams [29, 30]. It enables product developers to design as they are used to without needing to invest in new knowledge or alter manufacturing practices [14]. An example is the plant parts of LEGO, where LEGO replaced PE by bio-PE (Figure 5.5) [54].

Dedicated bio-based plastics, on the other hand, have no fossil-based equivalent, but offer novel properties that may better suit specific applications or provide environmental advantages [26, 31–33]. For example, the Skarvan Biobased Pants of Vaude (Figure 5.6) are made of the dedicated nylon PA6.10, which is lighter and has a higher fibre strength and elasticity than fossil-based PA [55]. However, adopting dedicated plastics often requires time and investments during the transition phase, as product developers need to acquire new knowledge. Current knowledge gaps about the performance of these newer materials causes product developers to often still be sceptical about the durability and performance of bio-based products [14, 15, 18], 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 are often lacking [26]. 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.

From an environmental perspective, the production of dedicated bio-based plastics is likely to be more efficient than that of drop-in plastics [26]. 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 [56]. In contrast, dedicated bio-based monomers use the carbon present in the biomass more efficiently [56, 57].

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 opportunities that dedicated bio-based plastics may bring.



Figure 5.5. LEGO plant parts made of bio-PE [54]



Figure 5.6. Vaude Skarvan Biobased Pants made of PA6.10 [55]

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

When product developers choose a drop-in bio-based plastic, 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 [34]. 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.

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 biobased (waste) material is added (e.g., used vegetable oil). The process results in different substances, e.g., monomers to produce plastics, but also low value molecules used for fuels. The proportion of bio-based feedstock entering the steam cracker is then allocated to a proportion of the outputs. In proportional allocation, bio-based credits are equally distributed over the output compounds, such as high-grade polymers or residues like fuel [35, 36]. 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% [35, 36]. 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 [35, 36]. In this scenario, the bio-based feedstock entering the system may actually never result in a proportion of bio-based content in the plastics, because it may end up largely in a side product of the production such as fuel. The term bio-based plastics is thus misleading and biomass balance of plastics can be considered greenwashing. A term that is increasingly used for mass balance plastics is bio-attributed plastics, which might be considered equally misleading 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 misleading. 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 [58].

5.4.5 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. Costs of biobased plastics are often higher than those of fossil-based alternatives and therefore may pose an important barrier for product developers [14, 15, 26]. The costs are relatively high because of factors like limited production scale, more complex manufacturing processes, and potential fluctuations in feedstock availability [10, 26]. 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 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 [10].

5.4.6 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 biobased plastics are sustainable, safe, and fully biodegradable [10, 37]. These claims can be deliberate (greenwashing) or may have been the result of widespread misunderstanding of the properties of biobased plastics among product developers [10, 14, 19]. 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 [10, 37, 59] and that biodegradable infers under natural circumstances rather than industrial composting, can lead to issues such as contamination in recycling streams or natural environments [10, 18]. Additionally, consumers associate terms like 'natural' and 'bio' with safety and health benefits, even when there is limited scientific evidence to support these claims [39]. This gap between perception and performance influences how products are received and can shape both consumer behaviour and market expectations.

5.4.7 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 [7]. For example, designing for recyclability may require avoiding certain additives or material blending that could complicate the recycling process [1]. 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, optimizing for a recovery strategy may compromise other aspects, such as functionality or environmental performance.

5.4.8 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 (see Figure 5.1). As the product and material lose their integrity, this is preferably one of the last recovery strategies to consider. However, there are applications, such as plastics that inevitably end up in nature, where this could be a suitable recovery strategy [60].

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 [42]. Biodegradation refers to the breakdown of a material by naturally occurring microorganisms such as bacteria, fungi, and algae [43]. 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 [45]. 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 [44], and industrial composting certifications allow for longer degradation periods than those typically applied in practice [6]. 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.

5.5 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 5.7 gives an overview of the considerations, guidance for product developers and enablers on macro level.

5.5.1 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 with consistent investment.



Figure 5.7. Life cycle guide for developing durable products with bio-based plastics: considerations (grey), guidance for product developers (blue) and enablers on macro level (green), mapped on the product life cycle of bio-based plastic products.

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 prioritize 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 [14]. If there are LCAs available, it can be valuable to work with LCA experts who then carefully evaluate the results, for example 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 actually adds value to a product and in which context the product should biodegrade (e.g., industrial composting facility or in soil) [1]. Durable plastic products should never be designed for disposal in nature when more valuable recovery strategies like recycling are possible [6]. 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 [60]. 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.

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 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 [15].

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 it may differ per country [10, 14, 18].

Consumers often form their views based on non-scientific information such as news reports, social media posts, and personal impressions [15, 18]. 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 [14, 18]. 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 also note that too much information, even if correct, can contribute to confusion [14]. 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 [61].

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 and transparent information should be communicated to consumers.

5.5.2 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 [10, 62]. 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 [10, 17].

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.

5.6 DISCUSSION

Product developers aiming to develop products with bio-based plastics face several knowledge gaps throughout the process. 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 [63]. While collaboration should be part of any product development process [64], 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 organization. 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 [6].

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 is a way to manage the risk of uncertainty, however, such collaborations can also introduce risks, such as dependence on a single supplier [65]. 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 [66, 67]. 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 [68–70].

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. While this guidance supports more informed decision making,

further progress will likely depend on sustained investment at both organisational and systemic levels.

5.6.1 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 [49]. 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.

5.7 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. 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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6

Discussion and conclusion

6.1 INTRODUCTION

This dissertation explored how bio-based plastics can be incorporated into the development of durable products designed for a circular economy. The research placed product developers at the centre of the analysis since their product design strategies and material choices influence how the products function within circular systems. In this context, we defined product developers as all stakeholders involved in the product development process, including management, material scientists, mechanical engineers, products designers and the purchasing department.

Bio-based plastics can support a circular economy. Derived from renewable resources, they can store carbon through processes like reusing, remanufacturing, or recycling products [1]. Preferably after multiple recovery cycles, the carbon embedded in bio-based plastics is eventually released into the atmosphere through biodegradation or incineration where it can be taken up by plants again, supporting a biogenic carbon cycle [2, 3].

To understand how to effectively incorporate bio-based plastics in product development, four studies were conducted. Table 6.1 summarizes the research questions and the main findings for each of the studies. In this chapter, the results of all four studies are synthesized and discussed to address the overarching research aim. Section 6.2 provides a summary of the main findings of the studies, followed by Section 6.3, which discusses the results in the broader circular economy perspective. Section 6.4 elaborates on the contributions to science, and Section 6.5 on the contributions to practice. Section 6.6 offers recommendations for further research, and Section 6.7 closes the chapter with concluding personal thoughts.

Table 6.1. Research questions and main findings of the studies in this dissertation

	Research Question	Main findings
Chapter 2	1 How are bio-based plastics perceived by actors throughout the value chain of durable consumers goods?	• Bio-based plastics are perceived as sustainable, even though actual environmental benefits are unclear. • Perceptions of bio-based plastics are often based on incomplete or incorrect information, leading to confusion, risks of greenwashing and incorrect disposal. • Actors find that consumers are interest in bio-based plastics, however, this rarely translate into actual purchases.
	2 What is the current state of the art of bio-based plastic use in durable consumer products?	• The use of bio-based plastics in durable consumer products remains limited and is primarily focused on drop-in substitutions with minor aesthetic changes. • Most of the bio-based plastics are made from 1st or 2nd generation feedstocks. • Focus in marketing mainly concerns the use of bio-based feedstock and not on recovery. • Sustainability claims are common but rarely backed by transparent, verifiable LCA data to support them.

Table 6.1. *Continued*

	Research Question	Main findings
Chapter 3	3 What are the opportunities and barriers faced by product developers in the use of bio-based plastics for durable consumer products?	• Using bio-based plastics is a way to reach corporate sustainability goals but companies encounter challenges due to a lack of supportive laws and regulations. • Drop-in plastics offer an easy transition from traditional fossil-based plastics, whereas dedicated plastics have a lack of recovery infrastructure and information on properties and processing. • Dedicated plastics can offer unique properties that can give innovative design possibilities. • High prices, limited availability, and costly R&D increase product costs, while consumers are generally reluctant to pay more. • Consumers often misunderstand the meaning of bio-based and biodegradable plastics, risking improper disposal. • Marketing around sustainability can backfire and result in greenwashing accusations.
Chapter 4	4 How can ambiently biodegradable plastics be applied in durable products that wear to reduce microplastic pollution in the environment?	• Ambiently biodegradable plastics currently have inferior mechanical properties compared to non-biodegradable alternatives. • Using ambiently biodegradable plastics challenges traditional durability-focused mindsets and require balancing product longevity with intentional biodegradation. • Accepting wear and incorporating the structural design principles of insulation (adding an extra layer), substitution (replacing wear parts), or product lifetime extension (restorative actions) can offer innovative solutions. • Designing with ambiently biodegradable plastics necessitates new business ideas, like new service models that could fit well with CE principles.
Chapter 5	5 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?	• Life cycle thinking is important in circular product development with bio-based plastics and should be embedded early in the design process. • Many barriers can be addressed through investment in time, resources, and knowledge development by companies and product development teams. • Guidance, such as advice on feedstock and material selection, could potentially support informed decision-making and help navigate the complexities of using bio-based plastics in durable, circular products.

6.2 MAIN RESEARCH FINDINGS

This section discusses the main findings of this dissertation and is structured according to the research questions presented in Chapter 1.

RQ1: How are bio-based plastics perceived by actors throughout the value chain of durable consumers goods?

Chapter 2 described a workshop with value chain actors of a telecommunications company, including people involved in R&D, legislation, management and sales. It revealed that while interest in bio-based plastics is growing, barriers exist at multiple points along the value chain.

Bio-based plastics were perceived positively as a more sustainable option. Participants believed bio-based plastic production can have a lower environmental impact than fossil-based plastic production. Furthermore, they saw it as a future-proof solution due to the use of renewable resources. It was indicated that consumers are also increasingly interested in sustainable solutions and therefore the use of bio-based plastics has marketing value. However, participants also indicated that although consumers express willingness to pay more, this rarely translates into actual purchasing behaviour, making the higher material costs a barrier for them.

Another driver mentioned was the innovation potential that a new material brings. For example, novel material properties of bio-based plastics can offer new design opportunities. In addition, their development could also provide opportunities for new collaborations and jobs. A key barrier identified was the general lack of knowledge about bio-based plastics among both consumers and value chain actors. Participants noted confusion between terms such as “bio-based” and “biodegradable” and uncertainty about the actual environmental benefits, increasing the risk of greenwashing. Concerns were also raised about recovery of bio-based plastics, as current recycling infrastructures do not always accommodate them.

External factors such as legislation and public demand were seen as stronger drivers for considering bio-based plastics than internal sustainability goals. Participants also emphasized the immaturity of the bio-based plastic supply chain, describing a “chicken or egg” problem: low demand limits investment and development, while the current high cost, knowledge gaps, and limited infrastructure discourage greater use.

RQ2: What is the current state of the art of bio-based plastic use in durable consumer products?

A design analysis of 60 products in Chapter 3 showed that bio-based plastics are beginning to find their place in durable consumer products. A few start-ups with sustainability missions have adopted bio-based plastics throughout their products, indicating a growing interest and early commitment to these materials. Larger companies are also starting to experiment, though typically on a smaller scale, by integrating bio-based plastics into a small part of their portfolio.

In most cases, bio-based plastics were applied as direct substitutes for fossil-based variants, with minor aesthetic changes such as green or pastel colours and

matte finishes. Four products in our sample made use of the unique properties of dedicated bio-based plastics to enhance product performance, which shows the opportunities for using these materials beyond simple substitution of fossil-based plastics.

Most of the plastics were made from first- or second-generation feedstocks, with castor oil and agricultural waste being the most common second-generation sources. Focus within marketing was mainly on the use of bio-based feedstock, sometimes suggesting that the use of these plastics was driven more by branding than by functional or sustainability benefits. Claims on sustainability were made but often lacked transparent LCA data to support them. End-of-life had less focus and if recovery was mentioned, it typically referred to the recyclability of drop-in bio-based plastics.

The transition to using bio-based plastics in durable products is clearly in its early stages, marked by small steps and sometimes unclear communication. However, the diversity of applications in our sample and the sustainability intentions of the companies involved offer a promising foundation for further development.

RQ3: What are the opportunities and barriers faced by product developers in the use of bio-based plastics for durable consumer products?

Interviews with product developers in Chapter 3 revealed several opportunities and barriers to the use of bio-based plastics in durable consumer products. Many interviewees expressed a sustainability vision and considered bio-based plastics as a way to accomplish this. They viewed these materials as a means to transition away from fossil resources and lower the carbon footprint of their products.

Despite this positive outlook, they also mentioned several barriers that they experienced. A key barrier identified was the lack of accessible, reliable information about bio-based plastics. Product developers noted uncertainty about the actual sustainability and environmental impact of these materials, as well as gaps in knowledge regarding their material properties and processing requirements. These uncertainties led to a preference for familiar drop-in bio-based plastics over novel, dedicated options. This preference was reinforced by the limited infrastructure for recovery and a lack of clear regulations, which made recyclable drop-in plastics a safer choice.

The absence of laws and regulations was also identified as a significant barrier to the widespread adoption of bio-based plastics. Product developers noted that clear, harmonized policies and standards for, e.g., the differentiation between plastics or recovery arrangements, are currently missing. Companies are waiting for rules, which slows development.

Limited material availability and high pricing, driven by a market dominated by a small number of producers, were also major concerns. Additionally, the high cost of research and development for novel bio-based alternatives further drives up product costs, while consumers remain hesitant to pay more. The interviewees also highlighted that consumers often lack a general understanding of what bio-based and biodegradable plastics are, possibly leading to incorrect assumptions and disposal.

Despite these barriers, the interviews reflected a motivation among product developers to work toward more sustainable solutions with bio-based plastics. Many are taking incremental steps but remain committed to exploring the potential of bio-based plastics.

RQ4: How can ambiently biodegradable plastics be applied in durable products that wear to reduce microplastic pollution in the environment?

Design explorations in Chapter 4 showed the potential of ambiently biodegradable plastics for use in durable products that wear, offering a promising strategy to reduce microplastic pollution. Ambiently biodegradable plastics are plastics that biodegrade in natural environments such as soil, freshwater and seawater, meaning they might also break down during use in these environments. This characteristic challenges both designers and users to move away from the traditional focus on durability.

Through design explorations of shoes, toothbrushes, and marine rope, a preliminary design framework was developed that helps navigate the trade-offs between the required durability and the temporality of ambiently biodegradable plastics. The framework (see Figure 6.1) emphasizes the need to incorporate circular design principles and proposes structural design strategies for components most prone to wear. The design strategy ‘insulation’ aims to protect the product from wear by adding an additional layer to the exposed surfaces, one that is biodegradable under ambient conditions. The strategy ‘substitution’ replaces materials of (part of) the product with ambiently biodegradable plastic. In the strategy ‘product lifetime extension’ restorative actions on the ambiently biodegradable plastic part are done to prolong the product lifetime. Understanding wear patterns becomes essential in identifying the best strategy to maintain the product's overall performance.

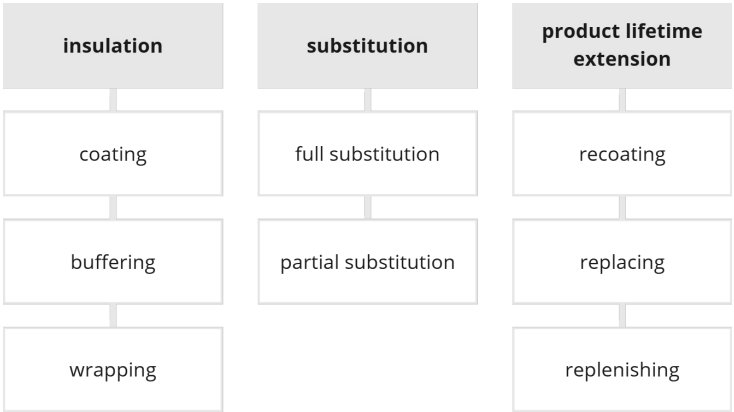


Figure 6.1. Design framework for using ambiently biodegradable plastics in products that wear

Designing with ambiently biodegradable plastics also introduces user behavioural and service-related challenges. Because these materials can degrade during use, changes in regular use and care routines may be necessary. To support this transition, design adjustments and new service models, such as modular replacements or take-back systems, can facilitate proper use and recovery.

There is a need to further develop ambiently biodegradable plastics, as currently available options face limitations. Their mechanical properties are generally weaker in comparison to their non-biodegradable counterparts, which might result in the use of more plastic overall and therefore accepting a higher environmental impact to avoid non-biodegradable microplastic release.

RQ5: What factors should product developers consider to effectively integrate bio-based plastics into circular product design?

The final study, presented in Chapter 5, builds on insights from the previous chapters by synthesizing key considerations for integrating bio-based plastics into circular product development. Many of these considerations were observed throughout earlier studies, and in Chapter 5 they are explored in greater depth with specific attention to their implications for product development and the role of product developers.

The study showed that product developers face several dilemmas or critical decision points that influence the product development process when working with bio-based plastics. These dilemmas often arise from trade-offs between competing priorities, such as performance, sustainability, and feasibility (e.g., cost constraints, supply chain availability, and manufacturing ability). Figure 6.2 presents a summary of the main considerations, guidance for product developers, and enabling conditions that lie beyond their direct influence.

The findings emphasized that bio-based plastics have the potential to support circular design goals. Their successful and sustainable use requires informed decision-making throughout the product life cycle. Embedding life cycle thinking from the early stages of development is important, especially as product developers must navigate challenges such as limited material availability, limitations in existing standards, and misconceptions among consumers.

Bio-based plastics are a promising pathway toward reducing reliance on fossil resources and enabling more circular practices. Dedicated investments in knowledge, time, and resources by companies and product development teams are needed. The guidance presented in Chapter 5 and visualized in Figure 6.2 offers a tool to support these efforts, helping product developers make informed decisions and manage the complexities of developing products with bio-based plastics for a circular economy.



Figure 6.2. Life cycle guide for developing durable products with bio-based plastics: considerations (grey), guidance for product developers (blue) and enablers on macro level (green), mapped on the product life cycle of bio-based plastic products.

6.3 BIO-BASED PLASTICS IN CIRCULAR PRODUCT DEVELOPMENT

Integrating bio-based plastics into circular product development presents both opportunities and challenges. Although this dissertation focused on durable products, many of the dilemmas identified, such as trade-offs between performance, sustainability, and feasibility, are also likely to recur in short-lived products like packaging. Barriers such as higher material costs may be even more pressing in these sectors, where products are typically low-cost and operate in competitive markets. Systemic limitations, like the lack of suitable recycling infrastructure, persist regardless of whether a product is short- or long-lived.

It is to be expected that biodegradability plays a different role in the use of bio-based plastics for short-lived products compared to durable products. While part of this research explored the tension between the need for longevity in durable products and the inherently temporary nature of biodegradability, this contradiction is largely absent in short-lived products. As a result, biodegradability (e.g., through industrial compostability) is sometimes proposed as a potential solution to waste associated with disposable products [4, 5]. Nevertheless, also for short-lived products, higher-value recovery strategies, such as reuse and recycling, should be prioritised where feasible to preserve product or material integrity. Moreover, promoting biodegradability as intentional recovery strategy in short-lived products may introduce additional challenges, particularly in terms of consumer perception. Consumers may be more inclined to dispose of single-use items in the environment if they are labelled as biodegradable, under the mistaken belief that they will naturally degrade without harm. Designing such products to degrade in open environments, through the use of ambiently biodegradable plastics, undermines more responsible disposal behaviours and risks contributing to long-lived microplastics in the environment [6].

Beyond the opportunities and barriers that arise during the product development process, there is also the fundamental question of whether and under what conditions using bio-based plastics is a sustainable choice at all. A key concern is the potential competition for renewable feedstocks with food production, land use and water resources, raising concerns about their social impact. Even second-generation feedstocks such as agricultural by-products, or third-generation sources like algae, come with trade-offs in terms of scalability, infrastructure, and potential indirect land-use changes. According to a recent report by the nova-Institute, meeting 20% of the chemical and material sector's total carbon demand with biomass by 2050 is realistic and achievable, without compromising the food and feed supply and the demand for biofuels [7]. However, there is a strong competition from Sustainable Aviation Fuels (SAF) which are backed by political support through quotas [7]. As demand for renewable resources increases, so does the pressure on the ecosystems that supply them. This highlights the risk of shifting the problem, where addressing one environmental issue (such as fossil resources dependency) may worsen others, such as biodiversity loss, land degradation, or water scarcity. Similarly, rebound effects can occur when efficiency improvements or more sustainable material choices lead to an overall increase in production or

consumption, negating the intended benefits [8]. This shows the need to look even further than the life cycle of a product and consider the broader system context.

For product developers, this adds yet another layer of complexity to the already challenging task of working with bio-based plastics in a circular economy. In this context, systemic design might offer a valuable perspective. The approach taken in this research already reflects a form of systemic thinking, as it considers interrelated factors across the micro (design process), meso (organization) and macro (external factors) levels. This perspective aligns with principles of systemic design, which encourages product developers to understand how their choices interact with wider social, ecological, and economic systems [9, 10]. Especially in the case of bio-based plastics, where impacts often stretch beyond the product itself, systemic design can potentially support more holistic and context-sensitive approaches. By embracing this broader view, product developers may be better equipped to navigate trade-offs.

6.4 CONTRIBUTIONS TO SCIENCE

This dissertation contributes to the field of circular product design with a specific focus on the use of bio-based plastics in durable applications. These contributions are structured around two main themes: (1) insights into the current use of bio-based plastics in durable products, and (2) analysis of how bio-based plastics might be effectively integrated into the development of durable circular products.

The research offers a design-centred understanding of how bio-based plastics are currently applied in durable products. This is a topic that has received limited attention compared to their use in short-lived applications like packaging. By analysing existing products and engaging with product developers, this dissertation highlights practical opportunities like the sustainability potential and challenges such as knowledge gaps and misconceptions. The findings identify several underexplored issues, such as material performance and environmental impact, that could enhance sustainable use of bio-based plastics through targeted research.

The research also introduces an exploration of ambiently biodegradable plastics in durable products that wear during use. The insights provide a novel design-oriented perspective on the use of these materials, where current research mainly focusses on material characteristics. Furthermore, most research around biodegradability focuses on short-lived, disposable products and this dissertation shifts the focus to durable applications. This opens a new research domain in which biodegradability is not only an end-of-life scenario, but a functional design strategy to mitigate microplastic pollution.

The dissertation advances scientific understanding by bridging the gap between material-focused research and design practice. It brings the product development perspective into bio-based plastic research and provides a structured overview of considerations relevant to product developers working with these materials.

6.5 CONTRIBUTIONS TO PRACTICE

In addition to its scientific contributions, this dissertation provides practical insights for product developers aiming to use bio-based plastics in durable applications. It offers guidance on key considerations when developing products with bio-based plastics. Product developers play a critical role in shaping how products function within circular systems, considering factors such as longevity, reparability, reuse, and the recoverability of materials. The guidance presented (see Figure 6.2), supports product developers in making informed decisions and navigating the complexities and uncertainties surrounding the use of bio-based plastics in circular product development. Furthermore, a design framework on designing with ambiantly biodegradable plastics (see Figure 6.1) is introduced to help product developers rethink wear and degradation in durable products. The framework offers strategies to integrate ambiantly biodegradable plastics to reduce microplastic pollution in the environment without compromising product function.

6.6 LIMITATIONS AND FUTURE RESEARCH

The research has several limitations that provide interesting directions for future research. A key direction for further investigation is the validation and refinement of the proposed guidance. The guidance developed in this dissertation (see Figure 6.2) represent an important first step in supporting product developers who are navigating the complexities of designing with bio-based plastics. However, the guidance has not yet been tested in real-world settings. Case studies involving actual product development projects would allow researchers to observe how product developers interpret, adapt, and apply the guidance in practice. Such studies could track the decision-making process over time, identify barriers or unintended consequences, and highlight where the guidance succeed or fall short in supporting sustainable choices. Case studies across diverse product categories and organisational settings would also reveal how different teams navigate, for example, trade-offs, regulations, and material constraints. This would not only improve the applicability of the guidance but also strengthen the bridge between scientific research and practical implementation.

Future research could focus on exploiting the unique properties of dedicated bio-based plastics. These plastics have unique properties compared to fossil-based plastics, however, these properties remain largely unexplored in durable products. Exploring how these properties can be intentionally used, rather than directly replacing fossil-based plastics, may open new design opportunities that align more closely with circular principles.

A scientific gap also lies in understanding biodegradation behaviour in ambient environments. As highlighted in this dissertation, some applications may benefit from the use of ambiantly biodegradable plastics that break down during wear. Yet, our understanding of how these materials perform in natural settings such as soil, marine environments, or freshwater is limited. Research into real-

world degradation processes is important for designing products that can safely biodegrade to the environment without contributing to microplastic pollution.

This dissertation has primarily focused on durable product development in a European context. Expanding the scope to include regions beyond the EU could offer valuable new insights into context-specific challenges, such as policy frameworks and recovery infrastructure. Separately, applying similar methods to short-lived products, such as packaging, may reveal distinct design considerations and recovery options. This could give insights into how certain dilemmas manifest differently depending on the product's lifetime and the context of use.

Finally, an area that remains underexplored is the intersection between user behaviour and product design from the perspective of product developers. Although consumer perceptions of bio-based plastics have been studied, little is known about how designers can support user understanding and behavioural change through, for example, product design. This becomes particularly important when bio-based plastics are used in products that require new patterns of use and maintenance, like with ambiently biodegradable plastics. Future studies could explore how product developers address these behavioural dimensions and how design can act as a communication tool to improve user acceptance and responsible use.

6.7 CONCLUDING PERSONAL THOUGHTS

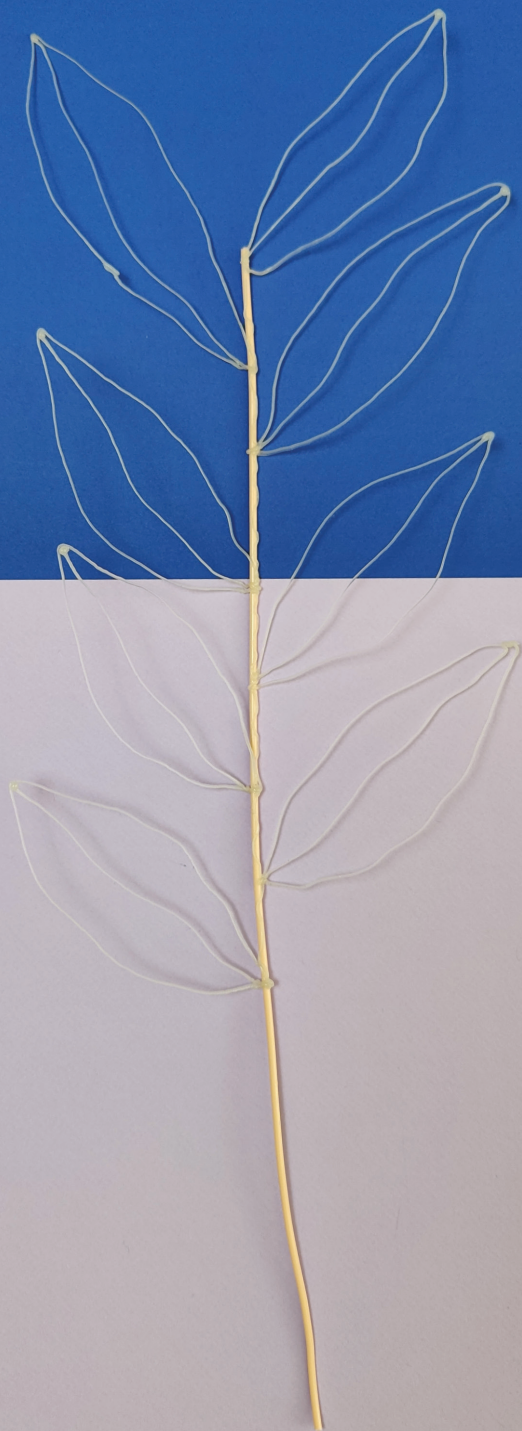
Over the past five years of working on this research project, I have witnessed significant changes in the field. On one hand, research into bio-based plastics has gained momentum, and interest in the circular (bio)economy continues to grow. On the other hand, practice still lags behind. While I have encountered genuine interest and goodwill from product developers, I have also seen how difficult it is for them to make informed decisions about using bio-based plastics. If there is one thing this journey has made clear to me, it is that the topic is complex and cannot be reduced to simple, one-size-fits-all advice. Emerging developments such as the biomass balance approach only add to this complexity.

I began this project with optimism, however, in recent years I have at times felt discouraged by the many barriers that stand in the way of a truly circular use of bio-based plastics. Political decisions that favour short-term fixes over long-term sustainability goals do little to ease the transition towards a bioeconomy. The tension between the need for short-term results and the slower pace of scientific contributions can be frustrating, especially when the urgency of environmental challenges calls for action. Nevertheless, I remain convinced that this transition is both important and achievable.

From the outset, my ambition has been to generate scientific insights in a way that supports practice, by bridging the gap between research and product development. I am pleased to have been able to realise this goal in the guidance presented. My hope is that these insights will contribute to the transition by better informing product developers, enabling them to make meaningful decisions that collectively support the larger systemic change.

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APPENDIX

APPENDIX A: DESIGN ANALYSIS RESULTS

Table A.1 presents the design analysis results. A larger version of the table can be found in the supplementary materials [1].

Table A.1. Design analysis results based on information available on corporate websites and reports, and interviews and articles in magazines.

[illegible]

*1	Adidas had a choose to give back program (Resale-as-a-Service) via the adidas Creator's Club app to be reused or resold
*2	Focus on CO ₂ footprint
*3	Focus on biodegradable
*4	Revivo program
*5	100% recyclable: complete shoe at ones. Recycle after +/- months/600 km
*6	Only available through subscription service, return when done with the product
*7	Repair service in place, unknown if pants will be recycled in their 'green shape' program
*8	Repair service in place, unknown if pants will be recycled in their 'green shape' program
*9	VEJA x Darwin, a test-hub for cleaning, repairing and recycling old sneakers. In shops in Paris, Bordeaux and New York.
*10	Revivo program
*11	'C-PLA is recyclable, but not in current disposal system.'
*12	The granulate is biodegradable, the end-product has no certificates yet
*13	Problem solving and repair tips per product on their website + spare parts available online
*14	Fujitsu has a WEEE-compliant take-back program in Europe + Trade-in Program
*15	Possible, but realize that current facilities are not handling these materials
*16	'A high proportion of plant material means that especially light-coloured products are more susceptible to discoloration and scratches'
*17	Can send back to recycle in their production. Get 30% voucher
*18	'Never leave your sunglasses inside the car as the temperature or direct heat from sunlight can cause damage to the frame and the lenses.'
*19	Made to last
*20	Repair service in place, unknown if pants will be recycled in their 'green shape' program
*21	Mattel PlayBack program in USA, Canada, France, Germany, UK: recycle materials and reuse in new products. Not possible: downcycle or energy recovery
*22	Reuse program currently only available in the US and Canada
*23	Mattel PlayBack program in USA, Canada, France, Germany, UK: recycle materials and reuse in new products. Not possible: downcycle or energy recovery
*24	Do not recommend reuse due to hygienic reasons (meant to be put in baby's mouth to relieve during teething)
*25	Unclear if Scarpa is using the 'Virtucycle Program' of material manufacturer Arkema
*26	Also in soil and water
*27	'We use granulate obtained from plants that are also native to our region'

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LIST OF PUBLICATIONS AND CONTRIBUTIONS

JOURNAL PUBLICATIONS

Bos, P.; van Dam, S.; Balkenende, R.; Bakker, C. (under review) Designing with Bio-based Plastics: Practical Guidance for Circular Product Development. *She Ji*

Bos, P.; Ritzen, L.; van Dam, S.; Balkenende, R.; Bakker, C. (under review) Exploring How to Avoid Microplastic Pollution through the Design of Products with Ambiently Biodegradable Plastics. *International Journal of Design*

Bos, P.; Ritzen, L.; van Dam, S.; Balkenende, R.; Bakker, C. (2024) Bio-Based Plastics in Product Design: The State of the Art and Challenges to Overcome. *Sustainability*, 16, 3295. <https://doi.org/10.3390/su16083295>

CONFERENCES & PRESENTATIONS

Conference paper at 5th Conference on Product Lifetimes and the Environment (PLATE), May 29 – June 2, 2023, Espoo, Finland. Ritzen, L., **Bos, P.**, Brown, P., Balkenende, A.R., & Bakker, C.A. (2023) Drivers and barriers for bio-based plastics in durable products. *PLATE 2023: the 5th Conference on Product Lifetimes and the Environment*. Retrieved from: https://www.plateconference.org/wp-content/uploads/2023/11/Plate_2023_proceedings.pdf

Poster presentation at The European Bioplastics Conference (EBC2023), December 12-13, 2023, Berlin, Germany. **Bos, P.**, Ritzen, L., van Dam, S.S., Balkenende, A.R., Bakker, C.A., Design potential of bio-based plastics for durable products

Exhibit as part of the 4TU.Design United exhibition at Dutch Design Week (DDW), October 21-29, 2023, Eindhoven, The Netherlands. **Bos, P.**, Bakker, C., Balkenende, R. & van Dam, S., Sole Survivor. <https://www.4tu.nl/du/projects/shaping-sustainable-futures/>

Conference paper and oral presentation at DRS Biennial Conference Series (DRS2022), June 25-July 3, 2022, Bilbao, Spain. **Bos, P.**, Bakker, C., Balkenende, R., & Sprecher, B. (2022) Bio-based plastics in durable applications: The future of sustainable product design? A design review. *DRS2022: Bilbao*. <https://doi.org/10.21606/drs.2022.284>

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ABOUT THE AUTHOR

Puck Bos was born on 29th of May 1990 in Naarden, The Netherlands. After completing secondary school at Griffland College in Soest, she went on to study Industrial Design Engineering at Delft University of Technology, where she earned both her bachelor's and master's degree. During her studies Puck completed internships at design agencies Studio Kees and Spark design & innovation, both based in Rotterdam. For her graduation project with Festo in Delft, she worked on the development of a double-acting muscle actuator with hygienic design, specifically tailored for application in the food and beverage industry. During this project, she applied the methodology of Nature Inspired Design.



After graduating in 2015, Puck returned to Spark design & innovation, where she worked as an industrial design engineer for five years. In this role, she was involved in a wide range of product development activities, including concept generation, prototyping, testing, and engineering for production. Motivated by an interest in sustainable product design and a desire to make it more accessible to designers, she returned to TU Delft in 2020 to pursue a PhD in the Design for Sustainability (DfS) group in the Faculty of Industrial Design Engineering.

During her PhD, Puck focused on the sustainable use of bio-based plastics for durable product development. She wrote several academic publications, presented her work at international conferences, exhibited at Dutch Design Week in 2023, and supervised students in courses and graduation projects. Alongside her academic work, she also became a mother to two sons, Guus en Bram, both born during her PhD.