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

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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.

Keywords: bio-based plastic; product design; circular economy; design analysis; sustainability transition; environmental impact

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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 [1]. 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 [2,3]. In 2022, approximately 1% of all plastic processed was bio-based, and their share is growing [4]. 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 [3]. 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 [5]. Today, bio-based plastics are mainly used in single-use applications [4,6]. 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 [7]. 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 [8].

The use of bio-based plastics could facilitate the shift towards a sustainable and circular economy, as they potentially have a lower environmental impact [9,10]. 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 [11,12]. 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 [13,14]. However, in order to ensure sustainability and circularity, feedstock sourcing and product and material recovery options need to be considered as well [13,15–17]. 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. [18] 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. [19] 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.

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.

2.1. Bio-Based Plastics

Bio-based plastics are plastics produced, at least partially, from renewable biological resources [2,3]. 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 [20] 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) [6,21]. The definitions we use are shown in Table 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 [22]. 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 [23]. 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 1. Overview of definitions related to bio-based plastics.

Bio-based plastic	Plastics produced, at least partially, from renewable biological resources [2,3]
Biodegradable plastic	Plastics that can be degraded by naturally occurring micro-organisms such as bacteria, fungi, and algae [20]
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) [6,21]
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) [6,21]

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 [24,25]. 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 [26] and needs large amounts of water and fertilisers [24]. 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 [24]. New developments have led to third generation feedstocks, which have the advantage that they do not require arable land and water for their cultivation [25]. 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 [27]. Each feedstock generation, therefore, seems to have its own advantages and disadvantages.

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 [28]. 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 1).

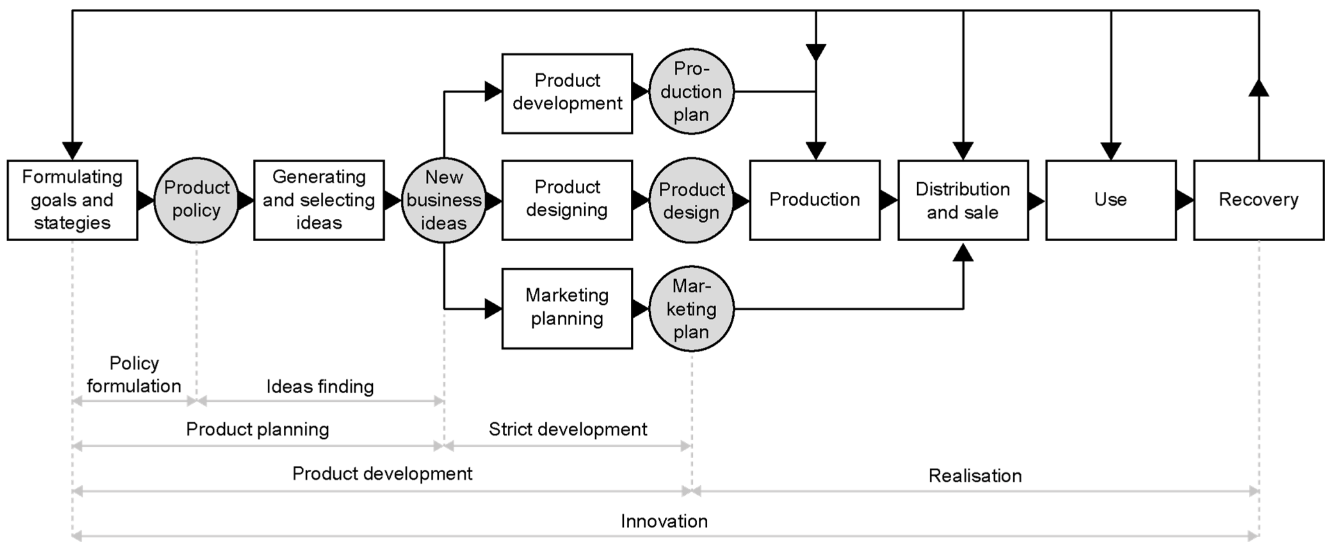

Figure 1. The Product Innovation Process model by Roozenburg and Eekels with the recovery step added [29]. The model shows all activities necessary to develop a new product for a market.

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 2 shows the research process flow.

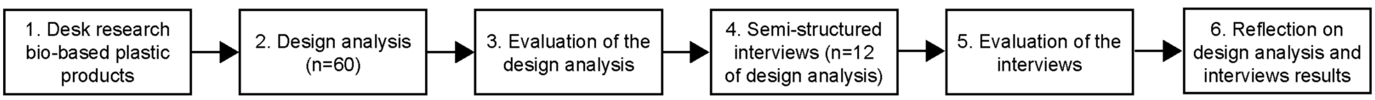

Figure 2. Research process flow chart showing principal steps.

3.1. Design Analysis

The design analysis followed the method as outlined in Bos et al. [30]. 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 [31] and Dezeen [32] and the website Bio-plastics News [33] 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) [5]. 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 [34], 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 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).

Table 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.

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.

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 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 [35] 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. Overview of the interview sample (I# = interview number, used for quotes in the result section).

I#	Interviewee(s) Position and Geographical Location *Western Europe (W-EU)* *Northern Europe (N-EU)* *East Asia (E-Asia)*	Company Size *Small (<10)* *Medium (10–100)* *Large (>100)*	Product Category	Bio-Based Plastic Type *Dedicated (D)* *Traceable Drop-in (T)* *Biomass Balance (B)*	
1	Product designer (W-EU)	small	Household appliances and utensils	PE	(T)
2	Co-founder, creative director, product designer (W-EU)	small	Household appliances and utensils	PLA	(D)
3	Founder, operational manager (E-Asia)	small	Toys and sports, Information and communication	PLA	(D)
4	Chief Executive Officer (CEO) (N-EU)	large	Household appliances and utensils	PA	(D)
5	Head of Materials (N-EU)	large	Toys and sports	PE	(T)
6	Head of R&D (W-EU)	large	Stationary and drawing	PHA 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 1). Table 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 [36]. This process resulted in opportunities and barriers linked to each process step in the Product Innovation Process model. As Corbin and Strauss [36] 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 4. Process steps of the Product Innovation Process model (see Figure 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.

4. Results

This chapter first presents the results of the design analysis in Section 4.1, then discusses the results of the semi-structured interviews in Section 4.2.

4.1. Results Design Analysis

During the design analysis, 60 products were identified. Table 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 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).

			Type of Bio-Based Plastic							
		Total per Category	**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 6 summarises the results of the design analysis per product category. The analysis per product can be found in Supplementary Materials Table S1. 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 packing of a product looked like, so it could not be determined whether bio-based was advertised on it.

Table 6. Design analysis results per product category (detailed results in Supplementary Materials Table S1).

		Aesthetics				**Functionality**						**Sustainability**									**Marketing and Communication**				
		Shape		Colour		Performance compared to fossil-based equivalent			Durability compared to fossil-based equivalent			Feedstock generation			Recovery mentioned by company						Bio-based communicated in/on:				
		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	Similar	Better	1st	2nd	3rd	Reuse	Repair	Recycle	Biodegrade	Incinerate	Recovery arrangements from company	Product	Product name	Description	Campaign	Packaging
Category	1	10	1	8	3		10	1		11		6	4	1	6	3	2	2	3	5	2	5	11	8	3
	2	5		3	2	1	4		1	4		4	1				1	4				3	5	3	1
	3	12	1	5	8	1	12		2	11		8	5		5	1	13				2	10	13	6	11
	4	6		4	2		5	1	1	5		3	3				3	5		2	4	4	6	3	4
	5	5		5			5		1	4		2	3		1		1				1	1	5	2	1
	6	17		9	8		15	2	1	16		11	6		6	1	13	3	4	4	1	10	17	6	15
	7	2	1	1	2		3			3		3			3			3			3	3	3	2	1
Total		**57**	**3**	**36**	**24**	**2**	**54**	**4**	**6**	**54**	**0**	**38**	**21**	**1**	**20**	**4**	**33**	**17**	**7**	**11**	**13**	**35**	**60**	**29**	**35***

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

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 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.

Figure 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 [37]. 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 [38]. 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 [39], Fujitsu's M440 ECO mouse had a soft touch feeling due to the cellulose used [40], 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 [41].

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 [42]. 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 [43]. 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 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 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.

4.2. Results of Semi-Structured Interviews

Opportunities for and barriers to using bio-based plastics were derived from the interview data. Table 7 presents an overview of all opportunities and barriers, divided into product innovation phases according to the adapted Product Innovation Model (Figure 2). 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 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

Table 7. *Cont.*

	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 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.

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.

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.

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.

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).

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.

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 [44]. 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 [45]. Reasons for the varying outcomes are the lack of a consistent methodology [11,12] and poor data availability for chemical conversion processes [11]. 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. [46] 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 [47] 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 [48]. Misleading marketing claims, intentional or unintentional, may also result in scepticism towards genuinely sustainable products, which can hinder their development [49]. The government can play a critical role by creating standards to counter misleading claims [50,51] and providing more guidance to consumers through clear, uniform labelling [14,52].

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 [53]. 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 [54]. 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.

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.

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.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16083295/s1, Description of interview results. Table S1: Design analysis results based on information available on corporate websites and reports, and interviews and articles in magazines. Refs [55–57] are cited in Supplementary Materials.

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Abbreviations

CA	Cellulose Acetate
EVA	Ethylene-vinyl acetate
PA	Polyamide
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
TPE	Thermoplastic elastomers

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