Bio-based plastics in durable applications: The future of sustainable product design? A design review

Bos, P.; Bakker, C.A.; Balkenende, A.R.; Sprecher, B.

DOI
10.21606/drs.2022.284

Publication date
2022

Document Version
Final published version

Published in
DRS Conference Proceedings 2022

Jun 25th, 9:00 AM

Bio-based plastics in durable applications: The future of sustainable product design? A design review

Puck Bos
Delft University of Technology, The Netherlands

Conny Bakker
Delft University of Technology, The Netherlands

Ruud Balkenende
Delft University of Technology, The Netherlands

Benjamin Sprecher
Delft University of Technology, The Netherlands

Citation

Bos, P., Bakker, C., Balkenende, R., and Sprecher, B. (2022) Bio-based plastics in durable applications: The future of sustainable product design? A design review, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), *DRS2022: Bilbao*, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.284

DRS 2022
Bilbao 25th June — 3rd July

Bio-based plastics in durable applications: the future of sustainable product design? A design review

Puck Bos*, Conny Bakker, Ruud Balkenende, Benjamin Sprecher

Delft University of Technology, Faculty of Industrial Design Engineering, Delft, The Netherlands

*corresponding e-mail: p.bos@tudelft.nl

doi.org/10.21606/drs.2022.284

Abstract: This design review evaluates the use of bio-based plastics in durable consumer products. The main question is: how does the use of bio-based plastics influence the product's design, functionality, marketing & communication, and sustainability? Although higher material prices would lead one to expect that higher value applications would be targeted, research shows bio-based plastics are mainly used in short-lived applications like packaging. This study investigates their use in durable consumer products through a design review. The results indicate that bio-based plastic usage is still in its early days in durable products. Bio-based plastics appear to be utilized as straightforward replacement of fossil-based plastic. Designers are not yet using the unique properties of bio-based plastics in the design of their products. Companies mainly exploit the green image of bio-based plastics in their marketing & communication. Their focus is on the renewable feedstock and not on sourcing, or on recovery at end-of-life.

Keywords: bio-based plastic; product design; design review; circular economy

1. Introduction

Plastics are a crucial material in our modern life and their use is growing every year. In 2019, almost 370 million tonnes of plastics were produced (PlasticsEurope, 2020). Most of these plastics are produced with fossil fuels, consuming ca. 6% of oil produced globally (Payne et al., 2019).

Growing concerns about climate change and plastic pollution (Jambeck et al., 2015) stimulate the development of alternatives to fossil based plastics (Bucknall, 2020; Kakadellis & Rosetto, 2021; Shen et al., 2010). One of these alternatives is bio-based plastic, meaning the plastic is made of renewable biological resources (Reddy et al., 2013; Zhu et al., 2016). Bio-based plastics can be divided into two groups: "dedicated" plastics which have a new chemical structure (e.g. PLA), and "drop-ins" with an identical chemical structure to their fossil-based equivalent (e.g. bio-PE) (Carus et al., 2017; IfBB, 2016). In 2020, approximately 1% of processed plastic was bio-based and their share is growing (Nova-Institute, 2021).

Bio-based plastics could potentially help in the transition towards a sustainable and circular economy, since they can be considered carbon-neutral (Haut et al., 2017; Spierling et al., 2018). The use of a renewable feedstock is necessary to move away from fossil fuels (Álvarez-chávez et al., 2012; Kakadellis & Rosetto, 2021; Mohanty et al., 2002). However, this alone does not necessarily make a product circular or sustainable (Venkatachalam et al., 2018). The type of feedstock has influence on the sustainability as well. For most plastics, either edible crops, so called 1st generation feedstock, or non-edible crops, 2nd generation feedstock, are used (Lambert & Wagner, 2017; Sheldon, 2014). New developments have led to 3rd generation feedstock where algae is used as feedstock (Lambert & Wagner, 2017). To make a bio-based plastic product circular, the environmental and technical impact of sourcing and recovery options should be taken into account (Bakker & Balkenende, 2021; Spierling et al., 2018). One could argue that good product design is crucial for achieving a true circular economy.

Although the current high costs of bio-based plastics would lead one to expect that higher value applications are targeted (Karan et al., 2019), research shows the bio-based plastics currently on the market are mainly used in single-use applications (IfBB, 2016; Nova-Institute, 2021). Indeed, the literature mainly focusses on short-lived applications like packaging instead of the use of bio-based plastics in durable products. Durable is defined here as products that can be used repeatedly or continuously over a period of a year or more, assuming a normal or average rate of physical usage (UNSD, 2018).

The aim of this research is to explore the current usage in durable products and how this bio-based plastic use influences the design, functionality, marketing & communication, and sustainability of the product.

We conducted a design review on a representative selection of consumer products made fully or partially of bio-based plastics. The selection of the products resulted from desk research to find bio-based products. In a design review, products are evaluated objectively against aspects related to product design.

2. Method

Desk research was used to find products fully or partially made of bio-based plastic. The research is limited to durable consumer products. The products were found by searching Google using terms like ‘bio-based plastic’ and ‘bio-based polymer’ in combination with the term ‘product’ or ‘design’. Additionally, the online magazines ‘Bioplastic magazine’ and ‘Dezeen’ and the website ‘Bioplastics News’ were used to find useful examples of bio-based plastic products. The search was limited to products available on the market in the past 10 years.

The research is qualitative, with a focus on design choices. The study is based on self-observation and reflection by the authors, based on information and pictures available on secondary sources. If a brand had a lot of similar products, for example different toys made from the same material, only one product was included. Similar products of different brands were not all included since no new insights would emerge from this. Only products of which the type of bio-based plastic was known were included. Information on the products and their bio-based plastic material had to be available in English for them to be included. The results were divided into categories according to 'Classification of Individual Consumption According to Purpose' (COICOP) (UNSD, 2018). The number of products is not representative of the bio-based plastic market as no exhaustive study was conducted.

Six cases were selected for the design review, which are representative of the products found during the desk research. We aimed to include products with different characteristics to include a diverse group of durable consumer products:

- Both drop-in bio-based plastics and dedicated bio-based plastics, to see whether dedicated bio-based plastics are used in a different way than drop-ins, i.e. not as direct replacements.
- Different generations feedstock (1^{st}, 2^{nd} and 3^{rd} generation), to see whether the choice of a more innovative feedstock leads to more innovative designs.
- Both successful and unsuccessful market introductions, to understand potential challenges companies face when introducing bio-based plastic products.
- Products used in extreme conditions (e.g. wear or temperatures), to explore to what extent the properties of bio-based plastics have been used to create heat-resistant or wear-resistant products.

These cases were reviewed by the authors on the following aspects: design, functionality, marketing & communication, and sustainability. These aspects were derived from the influence factors to the design process explained by Ashby and Johnson and on the first author's 5-year experience as industrial designer in a commercial agency. Ashby and Johnson state there are five dominant inputs that create the context in which design takes place; industrial design, technology, economics, the environment and the market (Ashby & Johnson, 2010). These inputs were taken into consideration while defining the review aspects explained in Table 1. With these review aspects, the influence of the bio-based plastic usage in the products was analysed.

Hereafter, a second set of six products were reviewed in less detail to verify the conclusions from the first set of products.

Table 1. Review aspects and how the products are reviewed.

Review aspect	
Design	The extent to which the product's aesthetics and texture - the 'look and feel' - seems to have been influenced by the use of bio-based plastics.
Functionality	The extent to which the properties of the product have, or have not, improved due to the use of bio-based plastics.
Sustainability	The deliberate choice of more sustainable forms of feedstock and the extent to which the end-of-life has been considered in the design and business model. (Note: no LCAs were made for the reviewed products in this research due to the lack of reliable information available.)
Marketing & Communication	The way bio-based plastics are marketed as an added value.

3. Results

In the desk research, 57 products were identified. Table 2 gives an overview of the product categories and the types of bio-based plastic. The results show bio-based plastics are used in a wide variety of applications. In most products only one type of bio-based plastic is used, of which the drop-in plastic PE and the dedicated plastic PLA occur most often. The majority of the products are in the categories 'Household utilities' and 'Recreation: Toys & sports'.

Table 2. Number of partially or fully bio-based durable consumer products included in the desk review: divided in categories and the bio-based plastics used.

			Type of bio-based plastic								
		Total per category	Cellulose	EVA	PA	PC	PE	PHA	PLA	PP	TPE
Category	Clothing & Footwear	***9***		2	2						5
	Furniture	***6***					1	1	3	1	
	Household utilities	***14***			1		9		4		
	Information & communication	***7***	1			2			1	1	2
	Recreation: Toys & sports	***14***			1		8		4		1
	Stationary & drawing materials	***3***						1	2		
	Personal effects	***4***	2		2						
Total		***57***	***3***	***2***	***6***	***2***	***18***	***2***	***14***	***2***	***8***

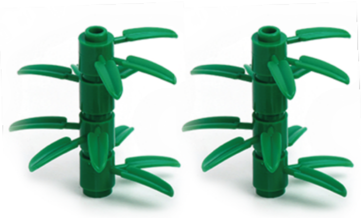
The first set of six cases that were selected for review from these 57 products are described, accompanied by a table with the design review results. Hereafter, the results of the first and second set of reviewed products are summarized in Table 10. Remarkable new results in the second set are added to the design review in the end of this section. Since the second set of products are less extensively reviewed, a number of questions remain open. These are indicated in the table with a question mark.

LEGO plants

The first products LEGO made from bio-based material are the plant elements. Fossil-PE is replaced by the drop-in bio-based PE, made from sugarcane, which is 98% bio-based (LEGO group, 2018). The products are released in 2018 and are sold in all LEGO sets containing plant parts.

Table 3. Design review 'LEGO plants'.

LEGO plants



bio-based (L) vs fossil-based (R) LEGO plant parts

LEGO plants advisement

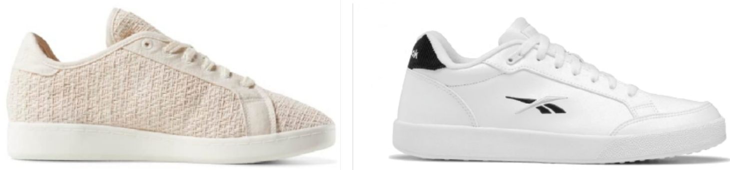
Design	The design of the plant parts remained the same when the fossil-based PE was replaced by bio-based PE.
Functionality	Drop-in bio-based PE performs the same as fossil-based PE and therefore the functionality and durability of the products did not change when switching to bio-based plastic.
Sustainability	The bio-based PE is made from sugarcane, a 1st generation feedstock. Bio-based PE can be recycled together with fossil-based PE.
Marketing & Communication	LEGO chose their plant parts as first products to use bio-based plastics; 'Plants from Plants'. The marketing is focused on the plant-based material, stating it is a sustainable material (LEGO group, 2018).

Reebok Cotton + Corn

The sole of the Reebok Cotton + Corn shoe is made from bio-TPU, which is made with 100% bio-based propanediol which is an ingredient of TPU (Susterra, 2018). Information about the other ingredients is lacking. If the TPU is a drop-in or a dedicated bio-based plastic and the bio-based percentage can therefore not be said based on the available information. The shoe was released in 2018 and is still on the market.

Table 4 Design review 'Reebok Cotton + Corn'.

Reebok Cotton + Corn



bio-based (L) vs fossil-based (R) Reebok shoes

Reebok Cotton + Corn advertisements

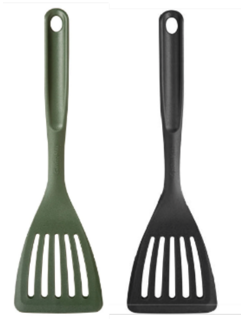
Design	In the Cotton + Corn shoe, Reebok uses a classic shoe design. The sole is bio-TPU derived from corn and the top is made from cotton. The cotton gives the product a natural look & feel. However, this is not because of the bio-based plastic used. The design of the sole and the shape of the shoe are not different from fossil-based Reebok shoes.
Functionality	Whether the bio-TPU is a drop-in or dedicated plastic is unclear. There are no indications that the performance and durability is different from fossil-based TPU shoe soles.
Sustainability	The bio-TPU is made from corn, a 1st generation feedstock. Although Reebok is saying it is working on completely home compostable shoes, the Cotton + Corn shoe is not. The soles are industrially compostable (Reebok, 2018). It requires specific circumstances to degrade, so micro plastics that are released through wear will not break down in nature.
Marketing & Communication	The bio-based content is used in the name of the product and in advertisements, focusing on the renewable content. Reebok acknowledges this is only a first step towards sustainable footwear (Reebok, 2018).

Orthex GastroMax Bio

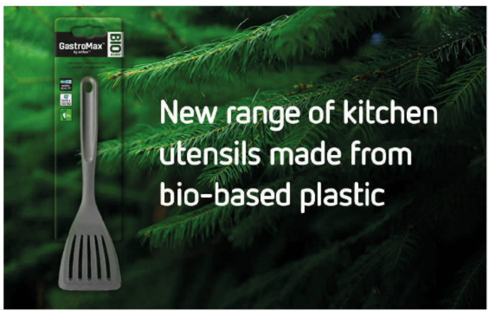
The kitchen utensils of Orthex GastroMax Bio are made of glass fibre reinforced PA derived from castor bean oil (DSM, 2021b). The PA is 70% bio-based (DSM, 2021a) and this specific PA, PA410, is considered a dedicated bio-based plastic (Carus et al., 2017). The products are released in 2020 and still on the market.

Table 5 Design review 'Orthex GastroMax Bio'.

Orthex GastroMax Bio



bio-based (L) vs fossil-based (R) Orthex kitchen utensils



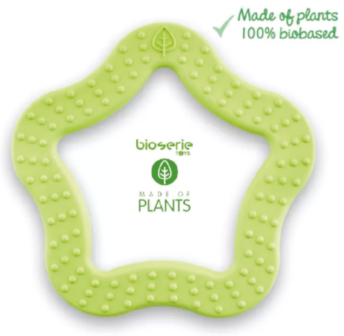
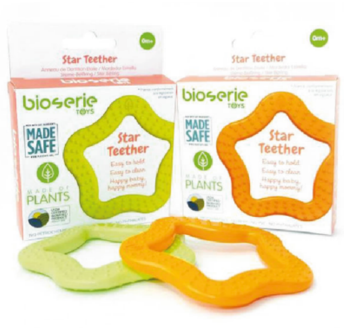
Orthex kitchen utensils advisement

	Orthex GastroMax Bio
Design	The shape and texture of the bio-based utensils are identical to the fossil-based utensils of Orthex. The only difference in the design is the colour; the bio-based products are green or grey and the fossil-based products are black.
Functionality	The bio-based utensils can withstand slightly lower temperatures; 210°C vs 230°C (Orthex Group, 2020b, 2020a). However, this is within the operating temperature of the product and will therefore not affect the durability of the product.
Sustainability	The bio-based PA is made from castor bean oil (DSM, 2021b), a 2nd generation feedstock. On the packaging and website the recycle symbol of PA is shown (Orthex Group, 2020b), implying the products can be recycled together with other fossil-based PA grades.
Marketing & Communication	The name of the product contains 'BIO'. A photo of branches is used as background on the packaging and the website. The packaging of the bio-based utensils expresses the natural origin of the material and shows a logo which states the bio-based product has a smaller carbon footprint. The website states a LCA is made. Only the main result is published: more than 50% carbon footprint reduction compared to fossil-based PA Kitchen utensils (Orthex Group, n.d.). It is unclear what data is used in the LCA.

Bioserie teether

All products of Bioserie are made of PLA, made from corn, and natural additives and organic colorants (Bioserie, n.d.-b). PLA is a dedicated plastic and 100% bio-based. The products are released in 2014 and still on the market.

Table 6. Design review 'Bioserie teether'.

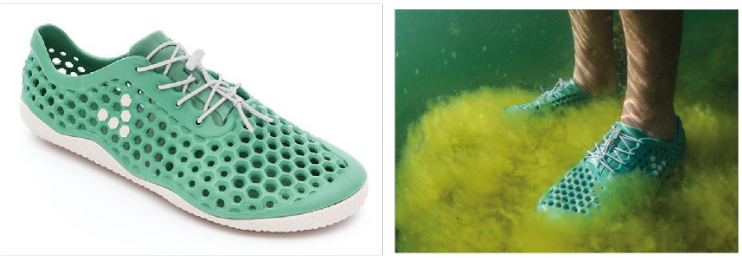
	Bioserie teether
	 *Bioserie teether advertisement*  *Bioserie teether packaging*
Design	The design of the teether does not refer to the bio-based plastic use. The teethers do not look different from other plastic teething rings.
Functionality	The teethers are hard plastic rings for baby's to bite on. The use of PLA does not make the function and durability of the product different from using other hard plastics approved for baby toys.
Sustainability	The PLA is made from corn, a 1st generation feedstock. Bioserie is stating three possible disposal options; 1. Incineration with energy recovery, gaining renewable energy 2. Recycling, although this option is limited in real life conditions 3. Composting in industrially composting facilities, which is still in early development stages (Bioserie, n.d.-a).
Marketing & Communication	The brand name contains 'bio' and on their website and packaging a logo 'made of plants' is displayed. In their marketing and communication the focus is on safe and healthy toys, because all the raw materials are derived from plants and do not contain oil-based chemicals (Bioserie, n.d.-b). It insinuates that oil-based chemicals are unsafe and unhealthy which is not necessarily the case. The health claim is not substantiated.

	Bioserie states that studies prove their material produces less greenhouse gasses and non-renewable energy than traditional polymers like polystyrene (Bioserie, n.d.-a).

Vivobarefoot Ultra III Bloom

The top of the Vivobarefoot Ultra III Bloom water shoe is made from bio-based EVA foam, which is 40% bio-based of which 5% is algae (Vivobarefoot, n.d.-a). Information about the exact ingredients of the material is lacking and therefore it cannot be said if the material is a drop-in or dedicated bio-based plastic. It is unclear if the use of algae changes the material properties compared to fossil-based EVA. The products are released in 2017 and still on the market.

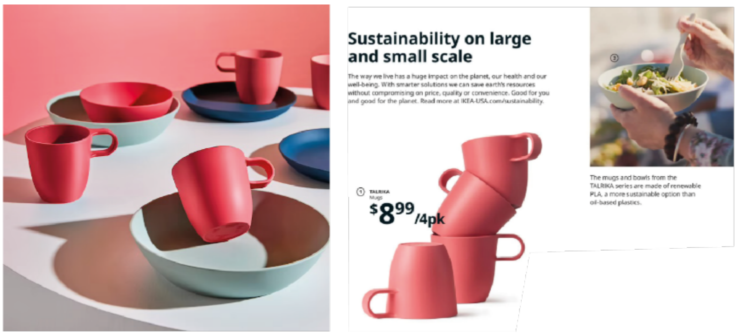
Table 7. Design review 'Vivobarefoot Ultra III Bloom'.

	Vivobarefoot Ultra III Bloom
	 *Vivobarefoot Ultra III Bloom advertisement*
Design	The organic structure in the design of the shoe refers to nature and an algae green colour is used.
Functionality	The use of bio-based EVA does not alter the functionality and durability in comparison to fossil-based EVA.
Sustainability	The material is partly bio-based. 5% is made from algae, a 3rd generation feedstock. EVA foam is difficult to recycle directly (Rosa et al., 2021). And because the EVA foam and sole from a different material are melted on each other, the shoe will not be recycled.
Marketing & Communication	The algae usage in the shoe is used in marketing and communication. Photos of the shoes in water with green algae blooms are used. The name 'Bloom' refers to algae bloom. Vivobarefoot is claiming using algae has a positive impact on the environment because removing algae cleans and restores the environment (Vivobarefoot, n.d.-b). The environmental impact is not fully substantiated.

IKEA TALRIKA

In 2019, IKEA released two series of products with plates, bowls and cups of PLA, made from corn; TALRIKA and HEROISK. Both were recalled in 2021 because products could possible break at elevated temperatures potentially causing burns (IKEA, 2021). PLA is a dedicated bio-based plastic. It is unclear if IKEA used a blend with specific additives.

Table 8. Design review 'IKEA TALRIKA'.

	IKEA TALRIKA
	 *IKEA TALRIKA folder advertisements*
Design	The design of the products is not different from similar fossil-based products.
Functionality	PLA turned out to be unsuitable for the application and the products had to be withdrawn from the market. They could not withstand high temperatures of hot food and beverages. PLA without specific additives to raise the heat resistance will start to deform around 60°C (Martin & Avérous, 2001). Consequently, the use of PLA decreased the durability of the product in comparison to similar products made from other plastics.
Sustainability	The PLA is made from industrial corn (IKEA, 2019a), a 1st generation feedstock . IKEA states their PLA products can be recycled (IKEA, 2019b). If the recalled products are recycled is unknown.
Marketing & Communication	IKEA does not exploit the bio-based plastic usage in their marketing and communication. It is only briefly mentioned in the description of the product on the website and in folders.

In line with these six products, an additional six were analysed to verify the findings of tables 3-8. An overview of the products of both sets is given in Table 9 and the results in Table 10.

Regarding the category 'Design' (see Table 10), the overall picture is that in most cases (10/12), the shape of the product is the same or similar to fossil-based equivalent products. If the colours are specifically chosen for the bio-based design, they are often green or pastel colours.

Most products (8/12) have similar functionality and durability compared to fossil-based equivalent products. In the second set of analysed products, there are two products which have a better performance according to the company. The Vaude Skarvan Biobased Pants made from bio-based PA are, among other things, said to dry faster and have a higher fibre strength (Vaude, 2020), and the bio-based TPE of the Scarpa GEA is claimed to be lighter (Scarpa, 2021).

Regarding 'Sustainability', more 2nd generation feedstock is used in the second set of prod-ucts (5/6). This is mainly waste material of edible crops. For the End-of-Life similar results are found in the second set as in the first set of products. Recycling is mainly mentioned as End-of-Life option (7/12). Though there are very few arrangements from the companies to ensure End-of-Life is done as intended.

Similar results for both sets were also found in Marketing & Communication. The bio-based content is displayed on the product, its packaging, in the product name, description and in the marketing campaign.

Table 9. Analysed products.

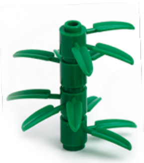
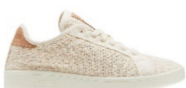
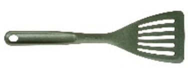
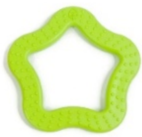
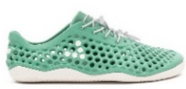
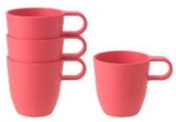
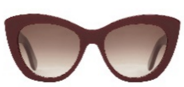
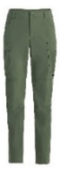
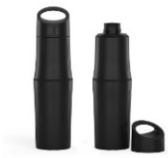
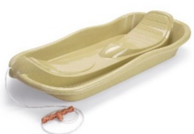
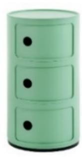
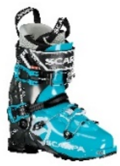
1st set					
1	2	3	4	5	6
LEGO plants	Reebok Cotton + Corn	Orthex GastroMax Bio	Bioserie teether	Vivobarefoot Ultra III Bloom	IKEA TALRIKA
					
2nd set					
7	8	9	10	11	12
Salvatore Ferragamo sunglasses	Vaude Skarvan Biobased Pants	BE O lifestyle BE O bottle	Dantoy Bio bobsled	Kartell Componibili Bio	Scarpa GEA
					

Table 10. Design review overview.

		Design				**Functionality**						**Sustainability**										**Marketing & Communication**				
		Shape		Colour		Performance (compared to fossil-based equivalent)			Durability (compared to fossil-based equivalent)			Feedstock generation			End-of-Life							bio-based communicated in/on:				
		Similar to fossil-based equivalent	Specific design for bio-based material	Similar to fossil-based equivalent	Specific colours for bio-based material	Similar	(Potentially) less	Better	Similar	(Potentially) less	Better	1st	2nd	3rd	Reuse	Repair	Recycle	Industrially compost	Biodegrade	Incinerate	End-of-life arrangements by company	Product	Product name	Description	Campaign	Packaging
1st set	1	x		x		x			x			x			x		x				x*			x	x	x
	2	x		x		x			x			x						x				x	x	x	x	x
	3	x			x	x			x				x				x						x	x	x	x
	4	x			x	x			x			x					x	x		x		x	x	x	x	x
	5		x		x	x			x					x						x	x		x	x	x	x
	6	x			x		x			x		x					x							x		
2nd set	7	x		x		x			x				x				?	?				?		x	x	?
	8	x			x			x	x				x			x	?				x**	x	x	x	x	?
	9		x	x		x			x				x				x					x		x	x	x
	10	x			x	x			x			x					x					?	x	x	x	?
	11	x			x		x			x			x						x			?	x	x	x	x
	12	x		x				x	x				x				x				?***	?		x	x	x

? Unclear wheter the product meets the critera
* Reuse program currently only available in the US and Canada
** Repair service in place, unknown if pants will be recycled in their 'green shape' program
*** Unclear if Scarpa is using the 'Virtucycle Program' of material manufacturer Arkema

4. Discussion

The aim of this research was to explore the current bio-based plastic usage in durable products and how this use influences the design, functionality, marketing & communication, and sustainability of the product.

Due to the higher price of bio-based plastics compared to fossil-based equivalents, exploitation in functionality and design of the products would be expected. However, in the reviewed sample of products, bio-based plastics appear to be utilized as a risk-free replacement of fossil-based plastic. Even for dedicated bio-based plastics that have unique properties compared to fossil-based plastics, one-to-one replacement seems to be the norm.

Adaptations to the design of the products are relatively minor. The bio-based origin of the plastic is sometimes expressed using soft pastel colours, the colour green or organic textures. This could indicate the emergence of new “bio” aesthetic, or merely an easy and cost effective marketing-related change. Another reason for the relatively minor changes could be that companies want to stay close to the designs the customers will recognise as products of their brand.

The limited utilization of bio-based plastic in the functionality of durable consumer products can be an indication that the use of bio-based plastics is still in its early days. One explanation could be that companies do not look beyond materials they know and are used to work with. Another possibility is that product designers are still learning about the properties. This can also be seen, for example, in automotive industry, where the use of bio-based plastics is currently mainly focused on non-structural interior components, but due to research & development and encouragements from governments, bio-based plastics are increasingly used in more structural parts like seat frames, load floors and steering components (Akampumuza et al., 2017).

As the market of bio-based plastics matures, exploitation of unique properties would be expected. For instance, using biodegradability where this might be useful, e.g. products or parts that are subjected to wear like tires or shoe soles. In the example of the bio-based soles of Reebok sneakers this is not yet the case, and it remains an open question whether it is technically possible. Further research is needed to discover which opportunities there are for using bio-based plastics in durable applications and what barriers are holding back industry from applying them more often.

A valuable property of bio-based plastic appears to be their good communicability. Bio-based plastic use is mainly exploited in marketing and communication of the products. The downside is that companies sometimes go too far with unsubstantiated and possibly misleading claims. Bio-based is communicated as equivalent to sustainable and safe. While it is likely a conscious choice to target consumers who are sensitive to such claims (enabling companies to increase prices or improve their sales), it could also be that expertise is missing and companies are not aware that their claims are incorrect.

Our design review indicates that there is little integrated thinking about the sustainability of bio-based plastics products. Companies seem to focus mainly on the bio-based origin of the material, but not on sustainable sourcing of the feedstock. The end-of-life and recovery pathways are often not communicated at all. If recovery options are mentioned, it is mostly theoretical (e.g. PLA is biodegradable or recyclable), but not how the product can be recovered in practice in a manner that is conducive to composting or high-quality recycling.

Challenges lie in designing with bio-based plastics considering the complete value chain in a way that ensures more sustainable product designs. This brings great responsibility to designers who are not only designing a physical product but who also have to think about sourcing and recovery after use. Further research into how designers can consider optimal circular economy routes is needed.

Obtaining information, especially details about the functionality and sustainability, from secondary data (e.g. websites) appeared to be difficult. Information was often in different places or not at all on the websites of the companies. The question is whether consumers take the effort to look beyond a product page or the information they see in the marketing material. This can create false expectations among consumers.

The design review was conducted with a desk review. In total 57 products were selected in the first stage, of which 12 products were reviewed in further depth. The results are limited by the available information online at the time of the search. They nevertheless are considered to provide insights that are relevant for the transition to bio-based plastics. Since the search concerned only English information, the results are mainly from Western countries. Geographical conclusion can therefore not be drawn. This design review was an exploratory study and presents many questions for further research.

5. Conclusion

This research set out to explore how the usage of bio-based plastics influences the design, functionality, marketing & communication, and sustainability of durable consumer products. The design review showed that there is not much evidence so far of creative use of the properties of bio-based plastics, with exception of marketing and communication. This indicates that the bio-based plastic usage in durable applications is still in its early days. Sourcing of sustainable feedstock and recovery of the bio-based plastics are hardly considered. While the focus of the industry currently seems to be on marketing and communication, there are almost certainly opportunities to make better use of the bio-based plastics in the design, functionality and sustainability of durable consumer products. Future research should set out to support product designers interested in these avenues of bio-plastics use.

6. References

Akampumuza, O., Wambua, P. M., Ahmed, A., Li, W., & Qin, X. H. (2017). Review of the applications of biocomposites in the automotive industry. Polymer Composites, 38(11), 2553–2569. https://doi.org/10.1002/pc.23847

Álvarez-chávez, C. R., Edwards, S., Moure-eraso, R., & Geiser, K. (2012). Sustainability of bio-based plastics : general comparative analysis and recommendations for improvement. Journal of Cleaner Production, 23(1), 47–56. https://doi.org/10.1016/j.jclepro.2011.10.003

Ashby, M., & Johnson, K. (2010). What Influences Product Design? In Materials and Design: The Art and Science of Material Selection in Product Design (pp. 8–27). Elsevier. https://doi.org/10.1016/b978-1-85617-497-8.50002-7

Bakker, C., & Balkenende, R. (2021). A renewed recognition of the materiality of design in a circular economy: the case of bio-based plastics. Materials Experience 2. INC. https://doi.org/10.1016/b978-0-12-819244-3.00020-x

Bioserie. (n.d.-a). FAQ. Retrieved November 19, 2021, from https://edu.nl/gdygw

Bioserie. (n.d.-b). Plant-Based Materials. Retrieved November 19, 2021, from https://edu.nl/qyvuj

Bucknall, D. G. (2020). Plastics as a Materials System in a Circular Economy. Philosophical Transactions of the Royal Society B.

Carus, M., Dammer, L., Puente, Á., Raschka, A., Arendt, O., & nova-Institut GmbH. (2017). Bio-based drop-in, smart drop-in and dedicated chemicals.

DSM. (2021a). EcoPaXX Q-KG6-FC. Retrieved from https://edu.nl/n6emb

DSM. (2021b). Spatulas and Kitchenware. Retrieved November 17, 2021, from https://edu.nl/gnhhh

Haut, G., Bolger, M., Alvarès, D. L., Blondeau, M., & Wachholz, C. (2017). Joint position paper. Bio-plastics in a Circular Economy: The need to focus on waste reduction and prevention to avoid false solutions. Retrieved from https://edu.nl/3hyhn

IfBB. (2016). Biopolymers facts and statistics 2016. Retrieved from https://edu.nl/yjr6a

IKEA. (2019a). IKEA Sustainability Report FY19. Retrieved from https://edu.nl/eqnuh

IKEA. (2019b). Only recycled or renewable based plastic in IKEA products by 2030. Retrieved November 17, 2021, from https://edu.nl/ntbkq

IKEA. (2021). IKEA recalls HEROISK and TALRIKA Bowls , Plates , and Mugs. Retrieved November 19, 2021, from https://edu.nl/t7aqm

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., … Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768–771. https://doi.org/10.1017/CBO9781107415386.010

Kakadellis, S., & Rosetto, G. (2021). Achieving a circular bioeconomy for plastics. Science, 373(6550), 49–50. https://doi.org/10.1126/science.abj3476

Karan, H., Funk, C., Grabert, M., Oey, M., & Hankamer, B. (2019). Green Bioplastics as Part of a Circular Bioeconomy. Trends in Plant Science, 24(3), 237–249. https://doi.org/10.1016/j.tplants.2018.11.010

Lambert, S., & Wagner, M. (2017). Environmental performance of bio-based and biodegradable plastics: The road ahead. Chemical Society Reviews, 46(22), 6855–6871. https://doi.org/10.1039/c7cs00149e

LEGO group. (2018). Plants from plants. Retrieved November 19, 2021, from https://edu.nl/hd7u9

Martin, O., & Avérous, L. (2001). Poly(lactic acid): Plasticization and properties of biodegradable multiphase systems. Polymer, 42(14), 6209–6219. https://doi.org/10.1016/S0032-3861(01)00086-6

Mohanty, A. K., Misra, M., & Drzal, L. T. (2002). Sustainable Bio-Composites from renewable resources: Opportunities and challenges in the green materials world. Journal of Polymers and the Environment, 10(1–2), 19–26. https://doi.org/10.1023/A:1021013921916

Nova-Institute. (2021). Bio-based Building Blocks and Polymers – Global Capacities, Production and Trends 2020 – 2025. Retrieved from https://renewable-carbon.eu/publications

Orthex Group. (n.d.). Our carbon footprint. Retrieved November 22, 2021, from https://edu.nl/8m93f

Orthex Group. (2020a). Slotted turner 29,5 cm. Retrieved November 11, 2021, from https://edu.nl/bxddg

Orthex Group. (2020b). Slotted turner BIO. Retrieved November 11, 2021, from https://edu.nl/7h7r9

Payne, J., McKeown, P., & Jones, M. D. (2019). A circular economy approach to plastic waste. Polymer Degradation and Stability, 165, 170–181. https://doi.org/10.1016/j.polymdegradstab.2019.05.014

PlasticsEurope. (2020). Plastics – the Facts 2020. An analysis of European plastics production, demand and waste data. PlasticEurope. Retrieved from https://edu.nl/fqkhf

Reddy, M. M., Vivekanandhan, S., Misra, M., Bhatia, S. K., & Mohanty, A. K. (2013). Progress in Polymer Science Biobased plastics and bionanocomposites : Current status and future opportunities.

Progress in Polymer Science, 38(10–11), 1653–1689. https://doi.org/10.1016/j.progpolymsci.2013.05.006

Reebok. (2018). Cotton + corn: explained. Retrieved November 17, 2021, from https://edu.nl/9ppcq

Rosa, V. B., Zattera, A. J., & Poletto, M. (2021). Evaluation of different mechanical recycling methods of EVA foam waste. Journal of Elastomers and Plastics, 53(7), 841–860. https://doi.org/10.1177/0095244321990400

Scarpa. (2021). GEA. Retrieved March 22, 2022, from https://us.scarpa.com/gea-1

Sheldon, R. A. (2014). Green and sustainable manufacture of chemicals from biomass : state of the art. Green Chem., 16, 950–963.

Shen, L., Worrell, E., & Patel, M. (2010). Present and future development in plastics from biomass. Biofuels, Bioproducts and Biorefining, 4(1), 25–40. https://doi.org/10.1002/bbb.189

Spierling, S., Röttger, C., Venkatachalam, V., Mudersbach, M., Herrmann, C., & Endres, H. J. (2018). Bio-based Plastics - A Building Block for the Circular Economy? Procedia CIRP, 69, 573–578. https://doi.org/10.1016/j.procir.2017.11.017

Susterra. (2018). Reebok Releases First Iteration of Revolutionary Plant-Based Footwear. Retrieved November 17, 2021, from https://edu.nl/qx9nq

UNSD. (2018). Classification of Individual Consumption According to Purpose (COICOP) 2018. Retrieved from https://edu.nl/pum8v

Vaude. (2020). Skarvan Biobased Pants – Trekking pants made of biobased polyamide PA 6.10. Retrieved March 22, 2022, from https://edu.nl/ard4m

Venkatachalam, V., Spierling, S., Horn, R., & Endres, H. J. (2018). LCA and Eco-design: Consequential and Attributional Approaches for Bio-based Plastics. Procedia CIRP, 69(May), 579–584. https://doi.org/10.1016/j.procir.2017.11.086

Vivobarefoot. (n.d.-a). BIO: WEAR MORE PLANTS. Retrieved November 11, 2021, from https://edu.nl/9ch84

Vivobarefoot. (n.d.-b). ULTRA III BLOOM MENS. Retrieved January 19, 2021, from https://edu.nl/tkda3

Zhu, Y., Romain, C., & Williams, C. K. (2016). Sustainable polymers from renewable resources. Nature, 540(7633), 354–362. https://doi.org/10.1038/nature21001

About the Authors:

Puck Bos is a PhD candidate at the Delft University of Technology. Her research focuses on developing guidance for product designers in using bio-based plastics for durable products in a circular economy.

Conny Bakker is professor of design for sustainability and circular economy at the Delft University of Technology. Her research focuses on design methods and strategies for circular product design.

Ruud Balkenende is professor for circular product design at the Delft University of Technology, focusing on design for a circular economy, emphasizing consideration of recovery pathways.

Benjamin Sprecher is assistant professor for circularity and sustainability assessment of product design at the Delft University of Technology. He specializes in the role of (critical) raw materials in socio-economic transitions.