MSc. Integrated Product Design Thesis
Faculty of Industrial Design Engineering
Delft University of Technology

Footprint For The Future, Exploring Bio-Based Biodegradable Plastics in Trail Running Shoes

Matteo Balboni

Delft, February 29th 2024

Master thesis
MSc Integrated Product Design
Matteo Balboni
5617111

Delft University of Technology
Faculty of Industrial Design Engineering
Langbergstraat 15
2624 CE Delft
The Netherlands

Chair
Dr. ir. Conny Bakker
Professor of Design Methodology for Sustainability and Circular Economy

Mentor
Ir. Puck Bos
PhD candidate at the Faculty of Industrial Design Engineering

Abstract

This research project explores the environmental issue of microplastic pollution, specifically focusing on its release from shoe soles into natural ecosystems. Despite increasing global awareness of microplastics, the particular impact of footwear, especially those used for outdoor activities in natural areas like trail running, has been largely overlooked. Microplastics released in these settings can directly impact ecosystems, affecting wildlife and soil health. This study investigates the potential of bio-based, biodegradable plastics, which can decompose harmlessly in soil, as an alternative material for trail running shoe soles. The aim is to mitigate harmful microplastic pollution and explore how the design of trail running shoes can be adapted to incorporate bio-based, biodegradable plastics.

The project begins by examining the problem of microplastic pollution, its origins, consequences, and the role of footwear. It distinguishes the difference between bio-based and petroleum-based plastics and the role of bio-based biodegradable and compostable plastics in embracing a circular economy. Through exploratory research, design iterations, prototyping, and critical analysis, this study evaluates the feasibility of using bio-based, biodegradable plastics in manufacturing trail running shoe soles. In fact, shoe soles have been identified as the primary source of microplastic pollution due to the constant abrasion with the ground.

A research was conducted in order to identify a bio-based soil-biodegradable plastic which could replace the currently used synthetic rubber. In terms of performance and environmental sustainability, PHA stands as the closest in meeting these criteria, yet it is not fully suitable for shoe soles application due to its limited flexibility.
Nevertheless, the project conceptualises “BioStep”, a trail running shoe that features a replaceable biodegradable outsole. The usage of such an outsole does not release any harmful microplastic when used during outdoor activities or in the decomposition process at the end of its lifespan.

This project sets the basis for the development of bio-based soil-biodegradable shoe soles for trail running shoes. Further research will be needed to identify a ready-to-use material and to address its performance in running scenarios.
Finally, this study emphasizes the need for collaborative efforts among designers, manufacturers, and material scientists to mitigate microplastic pollution and to set the path towards more sustainable footwear.

Preface

I conducted this research project as part of my MSc Integrated Product Design thesis, which represents my final academic assignment. My motivation behind this project was to explore how bio-based and biodegradable plastics can be utilised in everyday products to offer more sustainable scenarios and decrease our reliance on petroleum-based plastics and fossil fuels. Microplastics are a significant problem and they contribute every day to environmental pollution. Footwear is just one example among many others.

The journey was not without obstacles. The lack of readily available materials and the assumptions made beforehand created challenges during my design journey. Moreover, being the first time facing a footwear project, despite it being on my wish list for some time, made me realise the complexity of this product and the numerous aspects which need to be considered, especially when working independently.

My mentor, Puck Bos, and my chair, Conny Bakker, guided me through the project, which was fundamental in achieving the final result. Especially, when I found myself trying to solve too many problems at once and sometimes losing sight of the primary project scope. I am very thankful for their support.

After 20 weeks, this project has come to an end, and I have expanded my knowledge of bio-based, biodegradable, and compostable plastics. I now have a much clearer vision of the potential, current limitations, and future opportunities surrounding these materials, as well as useful design strategies for their proper application. This is an important step in my personal growth as a designer. Often there is confusion on these terms and how to select appropriate materials, taking into consideration the full lifecycle of the product, and not only the primary use. I am confident this knowledge will be useful in my career.

I would like to thank my girlfriend for her support over these five months. She tested every prototype, helped with collecting valuable feedback to improve each version from the beginning to the final design, and assisted in crafting the final version. My family also deserves deep thanks for their support throughout these months.

I hope you enjoy reading my project and appreciate the proposed concept as much as I enjoyed working on it over the past 20 weeks.

Table of content

Introduction

This research project aims to investigate the environmental issue of harmful microplastic pollution specifically focusing on its release through the abrasion of durable products, such as shoe soles. The study specifically focuses on trail running shoes, predominantly used in natural areas, where their pollution can directly contaminate the ecosystem (Forster et al., 2020). Despite the global awareness of microplastic pollution is widespread, the specific impact of footwear is often overlooked.

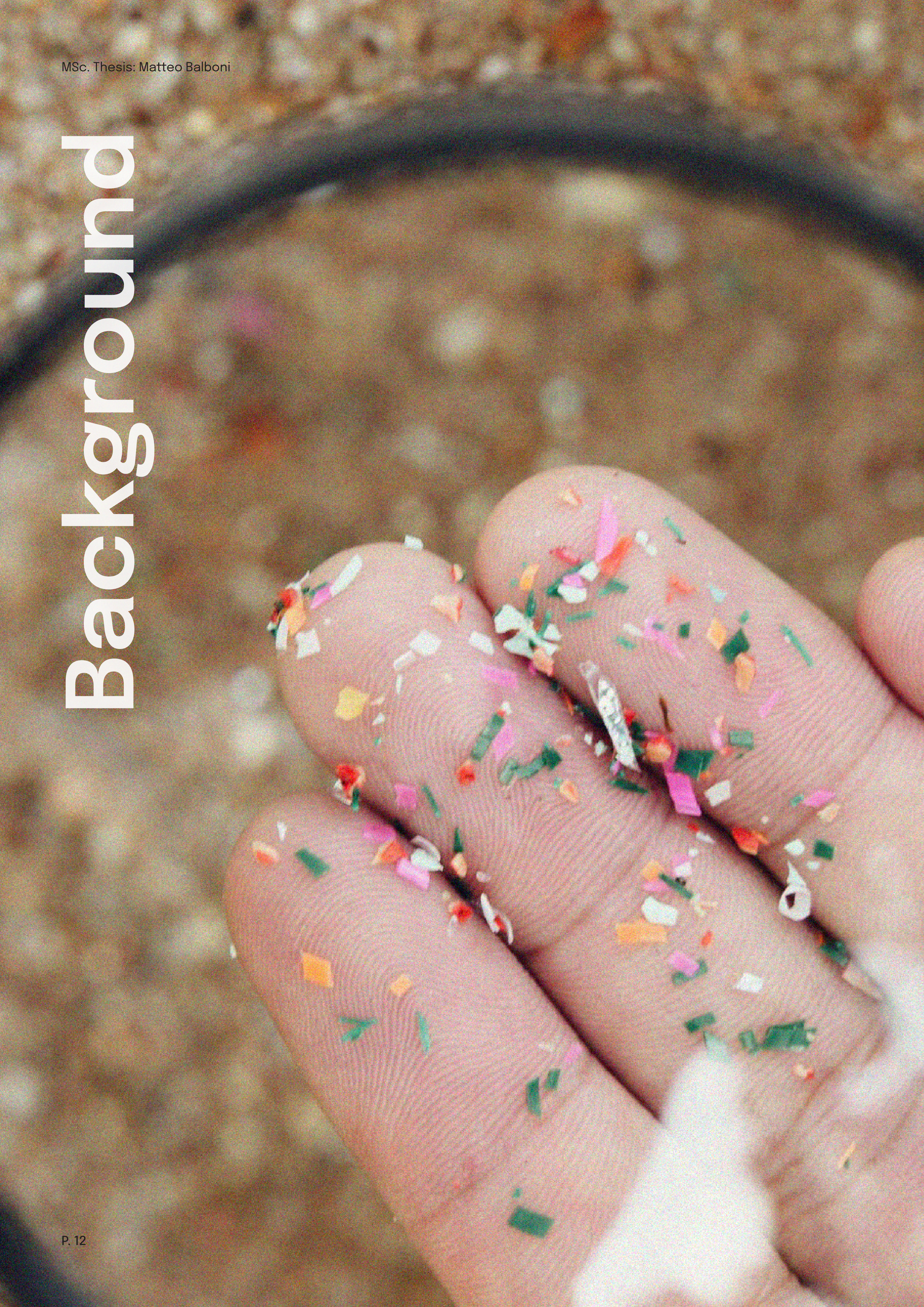
Currently, there are no trail running shoes on the market designed to completely eliminate the impact of microplastic release into the environment. These shoes typically prioritise functionality, and although some shoes incorporate recycled materials to promote sustainability, this approach is not always efficiently beneficial for the environment.

Most trail running shoes are composed of various materials bonded with glue, making their disposal and recycling complicated. As a result, at the end of their life, most of these shoes end up in landfills or are incinerated, contributing to environmental pollution and waste (Tonti, 2023; DiNapoli, 2024).
Furthermore, their use on uneven surfaces leads to rapid wear and tear. This not only results in a shorter lifespan compared to other types of footwear but also necessitates more frequent replacements by consumers (Sánchez, 2023).

Alternative materials like bio-based, biodegradable, and compostable plastics could offer a more sustainable option. Properties such as soil biodegradability may help with reducing the release of harmful microplastics from shoe soles in the environment and offer an alternative end-of-life option. However, the sustainability of a complex product, like shoes, not only depends on the materials used but also on its overall design.

This project investigates how the design of trail running shoes can evolve by using bio-based, soil-biodegradable plastics, to mitigate microplastic pollution and facilitate a sustainable recovery pathway for the end user.

Background



1.1 Background

This chapter provides essential background information necessary to understand the project. It begins with a brief overview of microplastics, highlighting the contribution of footwear to this form of pollution. Next, the chapter discusses bio-based plastics, explaining key terminology, the distinctions between bio-based and petroleum-based plastics, and how these materials can support a circular economy. Furthermore, the chapter highlights examples of companies that have successfully incorporated bio-based, biodegradable plastics into their footwear products.

1.2 Microplastics

Microplastics are defined as plastic pieces smaller than 5 mm and can take various forms, such as spheroids, fragments, or fibres and are composed of different polymers (Plastics Europe, 2022). A subset of microplastics, with a size of less than 0.050 mm, is known as nanoplastics (Lai et al., 2022).

Microplastic pollution has emerged as a significant environmental concern over the last few decades, primarily due to the extensive human reliance on plastic products (Rafa et al., 2024). Nowadays, microplastics have been detected in remote locations like the Arctic ice pack, as well as in human blood and breast milk (Hamzelou, 2023; Plastics Europe, 2022). Unlike larger plastic pieces, which are easily visible and removable, microplastics, due to their size, pose a significant challenge in detection and elimination (Yee et al., 2021).

These tiny particles are problematic because of their resistance to degradation, often requiring centuries to break down, causing long-term environmental harm (Plastics Europe, 2022).

1.3 The Impact of Footwear

Among the various products contributing to microplastic pollution through daily wear, shoe soles play a notable role. Although the wear and tear of shoe soles are commonly experienced, the implications of this process for microplastic pollution are often underestimated (Forster et al., 2020).

The Danish Environmental Protection Agency reported in 2015 that shoe sole abrasion in Denmark accounted for an annual release of between 100 and 1000 tons of microplastics (Lassen et al., 2015). Furthermore, a study in Germany in 2020 identified shoe sole wear as the seventh largest source of microplastic pollution in the country, estimating an annual release of 109 grams per capita (Bertling et al., 2018 as cited in Cecchi, 2023).

1.4 Bio-based plastics

Bio-based plastics are plastics that are either completely or partly made from biological sources, rather than from fossil raw materials. (European Commission, 2023). The term bio-based only refers to the origin of the material and does not necessarily mean that the product is biodegradable (Di Bartolo et al., 2021).

Bio-based plastics can be classified into two types: dedicated and drop-in (Ritzen et al., 2023). Dedicated bio-based plastics have unique chemical structures (Ritzen et al., 2023), such as PLA or PHA, while, drop-in bio-based plastics, on the other hand, have chemical structures identical to their fossil-based counterparts, but are made from renewable resources, such as bio-based Polyethylene (bio-PE) or bio-based polypropylene (bio-PP) (Ritzen et al., 2023).

Drop-in bio-based polymers have the advantage of easily fitting into existing recycling processes which are meant for similar petrochemical products (Ritzen et al., 2023). On the other hand, dedicated polymers can be used to produce products that cannot be obtained through traditional chemical reactions and products that may offer unique and superior properties, otherwise impossible with fossil-based alternatives (Carus et al. 2017).

1.4.1 Terminology clarification: bioplastic, biodegradable, and compostable plastics

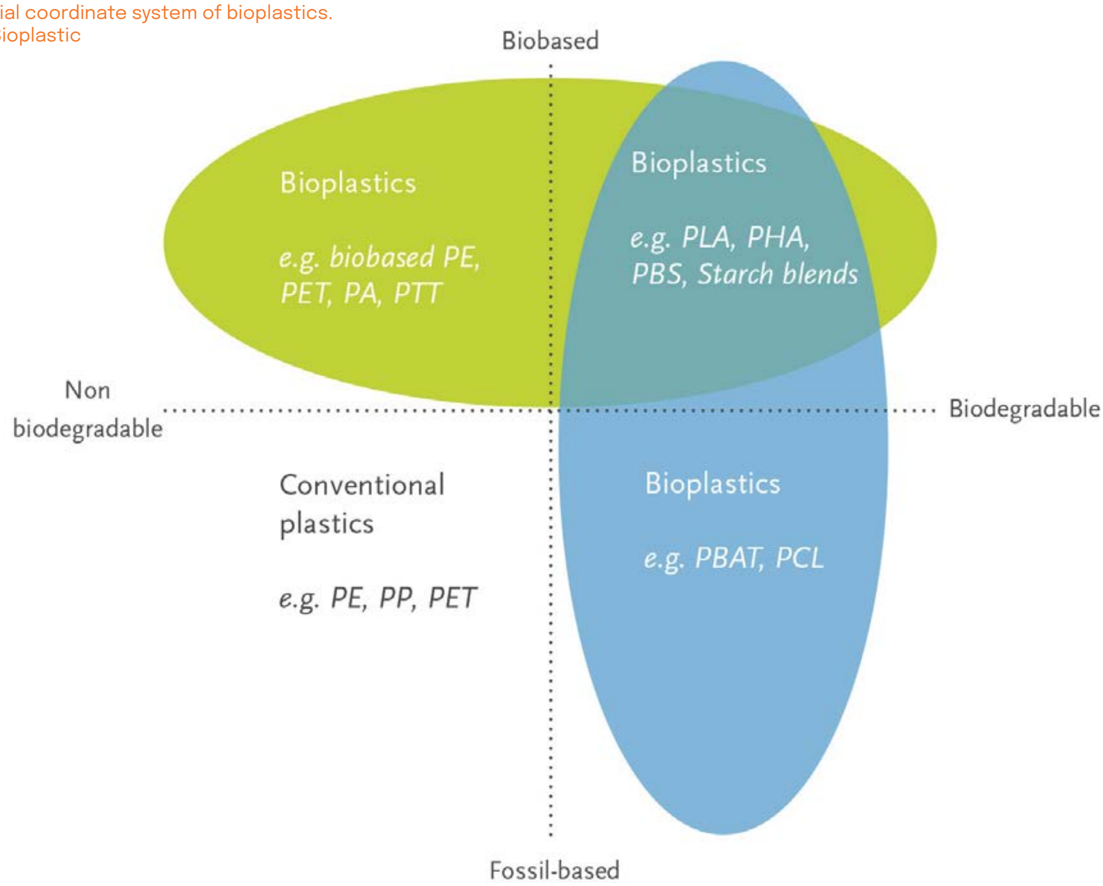
The term bioplastic is not interchangeable with the terms bio-based, or biodegradable. The term bioplastics refers to a broader category of plastics that can be either bio-based but not biodegradable, bio-based and biodegradable, or fossil-based and biodegradable, (Al-Khairy et al., 2022) as depicted in Figure 1.

Biodegradability refers to the process by which a plastic is designed to decompose into natural substances like water, carbon dioxide, and compost. This decomposition is facilitated by microorganisms in specific environments such as water, soil, or compost, under certain conditions (European Environmental Agency, n.d.; European Bioplastic, n.d.-a).

1.4.2 Soil biodegradable plastics

Soil-biodegradable plastics are engineered to decompose upon contact with soil at the end of their life cycle without harming the environment (Briassoulis & Innocenti, 2017).

▶ Fig. 1 Material coordinate system of bioplastics. European Bioplastic



These plastics find utility in various applications, including products designed for direct soil contact like agricultural mulching films, or for instance, where soil is the ultimate endpoint, such as in clay target shooting (Briassoulis & Innocenti, 2017). Therefore, given the inevitable wear and tear of shoe soles in natural settings, these biodegradable materials hold the potential for significantly reducing environmental impact.

However, soil quality plays a significant role in this context, as it serves as a disposal medium for soil-biodegradable plastics. The rate at which bio-based materials decompose is influenced by the molecular structure of the soil and by environmental conditions including temperature, moisture, and oxygen availability, which in turn affect microbial activity (Briassoulis & Innocenti, 2017).

Thus, the development of biodegradable plastics has emphasised the need for standardisation to ensure market transparency, as consumers cannot directly assess biodegradability (Briassoulis & Innocenti, 2017). Standard tests measure biodegradation potential under controlled conditions but do not set a definitive pass level (Briassoulis & Innocenti, 2017). Instead, “standard specifications” establish criteria for what can be classified as “biodegradable” in soil (Briassoulis & Innocenti, 2017). These tests aim for repeatability, but may not fully mimic actual soil conditions.

Currently, there are no European or international standards that define the biodegradation criteria for bio-based products in soil environments, though France and Italy have established their own national specifications (Briassoulis & Innocenti, 2017).

1.4.3 Compostable plastic: Industrial vs home composting

Compostable plastics are specific types of biodegradable plastics, defined by their ability to break down in composting environments and leave behind only beneficial substances like fertiliser, without any toxic residue (European Commission, 2023). Thus, while all compostable plastics are biodegradable, not all biodegradable plastics are compostable.

The process of composting can occur under two conditions, industrially or at home.
In industrial composting facilities, specific conditions are used, including controlled temperature, humidity, and aeration, to efficiently break down plastics. Therefore, industrial compostable plastics cannot decompose naturally in the environment, but only under specific conditions found in composting facilities (European Bioplastic, n.d.-b).

In contrast, home composting can occur in proper domestic compost bins, since home compostable plastics require less stringent conditions, such as lower temperatures. However, the majority of plastics labelled as ‘home compostable,’ can also be degraded in industrial settings (European Environmental Agency, n.d.; European Bioplastic, n.d.-b)

▶ Fig. 2 Industrial compostable facility

1.4.4 Compostable Plastics in Footwear

Industrial compostable plastics have been explored in the context of footwear, particularly by the company Balena. They have developed a new material, BioCir, leading to the creation of a fully industrially compostable slipper, a shoe sole, and a 3D-printed hiking shoe in collaboration with Vivobarefoot (Balena Science, n.d.) This project aims at reducing both the carbon footprint and the number of shoes accumulating in landfills through a different end-of-life scenario, namely industrial compostability.

Other companies in the market offer similar alternatives. BlueView sells a fully biodegradable shoe; the sole is made of Soleic, a plant-based polyurethane derived from plant oils, and the upper part is made in knitted hemp and eucalyptus (BLUEVIEW | Sustainable Shoes & Biodegradable Footwear, n.d.).

The Portuguese company ForEver exclusively specialises in making soles and outsoles and has a product called "Infinity Biodegradable," which is certified with the standard EN 14995 (For Ever®, n.d.). Additional information about the standard system is presented in the following chapter. However, to obtain such a certification, additional substances such as glue and colourant, if used, must also be fully compostable (Federation, n.d.).

Nevertheless, plastics that are compostable in industrial settings do not naturally decompose in the environment and must be properly collected to undergo the composting process. Consequently, microplastics released from these materials may still pose environmental risks. Similarly, plastics designed for home composting, which break down under less stringent conditions and at lower temperatures, may not fully degrade in natural environments. Nowadays, multiple

▶ Fig. 3 Balena Vivobarefoot, 3D-printed compostable shoes

▶ Fig. 4 Balena BioCir Slides

▶ Fig. 5 BlueView shoes

studies are assessing the long-term effects of microplastics derived from compostable plastics on the environment.

1.4.5 Bio-based Plastics standards

Identifying bio-based plastic products on the market can be challenging due to their similar appearance to conventional plastics (European Bioplastic, n.d - c.). Therefore, internationally recognized labels are used to inform consumers about the nature of the product, which is essential for proper disposal (European Bioplastic, n.d.). Several global organisations, including the European Standard (EN), the American Society for Testing and Materials (ASTM), the International Organization for Standardization (ISO), and TUV AUSTRIA, have established standards for compostable product certifications (Team, 2023).

Nowadays, two key standards stand out for their international recognition and compliance with compostability standards: the EN 13432 and the EN 14995.

EN 13432 standard applies specifically to packaging and it requires that every component of it, including colours, labels, glues, and residues, can be industrially composted. Only packaging that disintegrates within 12 weeks and biodegrades completely within six months is certified as EN 13432 (European Bioplastic, n.d.a; n.d.b).

EN 14995, on the other hand, evaluates the compostability of non-packaging plastics. This standard uses the same testing methods and criteria as EN 13432 but applies to any plastic material or product not used for packaging (Federation, n.d.).

▶ Fig. 6 ForEver, Infinity Biodegradable sole

1.4.6 Labels

1.4.6.1 Biobased content

Manufacturers of bio-based plastics and content are not obligated to reveal the precise quantity of bio-based materials incorporated into their products. However, they may choose to provide this information voluntarily to support their claims. In Europe, two organisations offer certifications and corresponding labels based on a European standard* (European Bioplastic, n.d.c; TÜV Certifications, n.d.).

*CEN/TS 16137:2011 Plastics – Determination of biobased carbon content

1.4.6.2 Industrially compostable

For industrially compostable products, widely recognized labels include the Seedling logo and the OK Compost industrial logo (FigX). These certifications are provided by TÜV Austria Belgium and DIN CERTCO (European Bioplastic, n.d.c).

1.4.6.3 Home compostable

While there is no global standard for home composting, several countries have developed their own standards. The OK compost home certification by TÜV Austria Belgium, for instance, requires at least 90% degradation within 12 months at ambient temperature (European Bioplastic, n.d.b). It is possible to find packaging with EN 13432 certification also labelled as "home compostable", if it meets specific compostability properties (Federation, n.d.).

1.4.6.4 Biodegradable in soil

The OK biodegradable SOIL label from TÜV Austria Belgium ensures products biodegrade in soil without environmental harm, requiring at least 90% biodegradation within two years (TÜV Certifications, n.d.). This certification is mostly found in agricultural products. The standard EN 17033 applies to mulch films only, however, other products can be certified on request, with additional ecotoxicity tests (European Environmental Agency, n.d.; OK Biodegradable Soil, n.d.).

1.4.6.5 Biodegradable in water

There is currently no European standard for water biodegradability due to the varying conditions in freshwater and marine environments. However, TÜV Austria has developed a certification scheme.

OK Biodegradable Water indicates products that biodegrade 90% in freshwater within 56 days (OK Biodegradable Water, n.d.).

The OK biodegradable MARINE label, developed by TÜV AUSTRIA, does not have a European standard. The previous US standard (ASTM D7081) was withdrawn in 2014 without a replacement (European Bioplastics, 2023).
The certification requires at least 90% biodegradation within six months (European Bioplastics, 2023).

Fig. 7 A waste bag certified as compostable for both home and industrial settings

1.4.7 Current Limitations & future perspective

Bio-based biodegradable plastics are finding increasing use, particularly in sectors such as food packaging, food and beverage products, shopping bags, and agricultural films, where they serve as alternatives to single-use plastics (Van Den Oever et al., 2017). For food-related packaging, compostable plastics offer the advantage of being compostable along with any residual food waste, reducing landfill contributions and preventing the contamination of recycling processes with food waste (Oakes, 2022).

In agriculture, materials certified as soil-biodegradable, like plastic mulch films, which are traditionally made of Polyethylene (PE), are used to enhance crop yields and water conservation. However, they leave behind residues that contribute to microplastic pollution. Biodegradable alternatives that decompose through soil microorganisms offer a solution by preventing the accumulation of microplastics in the environment (Guliyev et al., 2023; Van Grinsven & Schubert, 2023).

Despite their benefits, bio-based, biodegradable plastics face challenges. Part of them (dedicated polymer) can disrupt the current plastic recycling processes, as they are incompatible with petroleum-based plastics, risking contamination in the recycling process (Alaerts et al., 2018). Notably, for instance, PLA (polylactic acid) significantly disrupts PET (polyethene terephthalate) recycling, requiring a separate recycling process. However, to be economically feasible, bio-based plastic recycling needs to happen on a large scale (Alaerts et al., 2018).

Furthermore, the higher cost of bio-based and biodegradable plastics compared to petroleum-based alternatives can pose an additional challenge, potentially limiting their widespread application and preference over standard plastics (EuroPlas, 2023).

Bio-based and biodegradable plastics currently represent only 0.5% of more than 400 million tonnes of plastic produced in 2022. Nevertheless, their production capacity is expected to grow significantly, with an estimated increase to 7.43 million tonnes by 2028 (European Bioplastics, n.d.-e), indicating a promising trend for the future.

Fig. 8 Global production capacities of bioplastic, European bioplastic

1.4.8 Bio-based plastics & circular economy

Bio-based plastics are considered a key component in the circular economy being fully or partially made from renewable resources. (Ritzen et al., 2023). In contrast to petroleum-based plastics, bio-based plastics typically have a lower carbon footprint, saving fossil fuels and reducing greenhouse gas emissions (Guliyev et al., 2023). Some bio-based plastics can seamlessly fit into current recycling processes (dedicated polymer), and some others provide biodegradation as an end-of-life option under controlled or predictable conditions (Rosenboom et al., 2022).

According to the Ellen Macarthur Foundation, the definition of circular economy is the following:

"The circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting".

The circular economy is based on three fundamental principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value) and regenerate nature (Ellen MacArthur Foundation, n.d.).
This system is the opposite of a linear economy, in which products are purchased, used, and then discarded (Knight, 2023).

The butterfly diagram is a visualisation by the Ellen MacArthur Foundation, commonly used to visually represent the continuous circulation of materials within a circular economy. This diagram delineates two key cycles: the technical and the biological.

In the technical cycle, products and materials are maintained in usage for as long as possible through practices such as reuse, repair, remanufacturing, and recycling. Technical cycles are usually for products made from non-biodegradable materials. (Ellen MacArthur Foundation, n.d.)

The biological cycle, on the other hand, emphasizes the process of returning nutrients from biodegradable materials to the Earth, promoting natural renewal. (Ellen MacArthur Foundation, n.d.) This process enables the land to restore its nutrients, which can subsequently be utilized to produce new biodegradable materials, thereby securing the cycle's sustainability. (Ellen MacArthur Foundation, n.d.)

Some biodegradable substances, like cotton or wood, could transition from the technical cycle to the biological cycle after they have deteriorated to a stage where they are no longer viable for

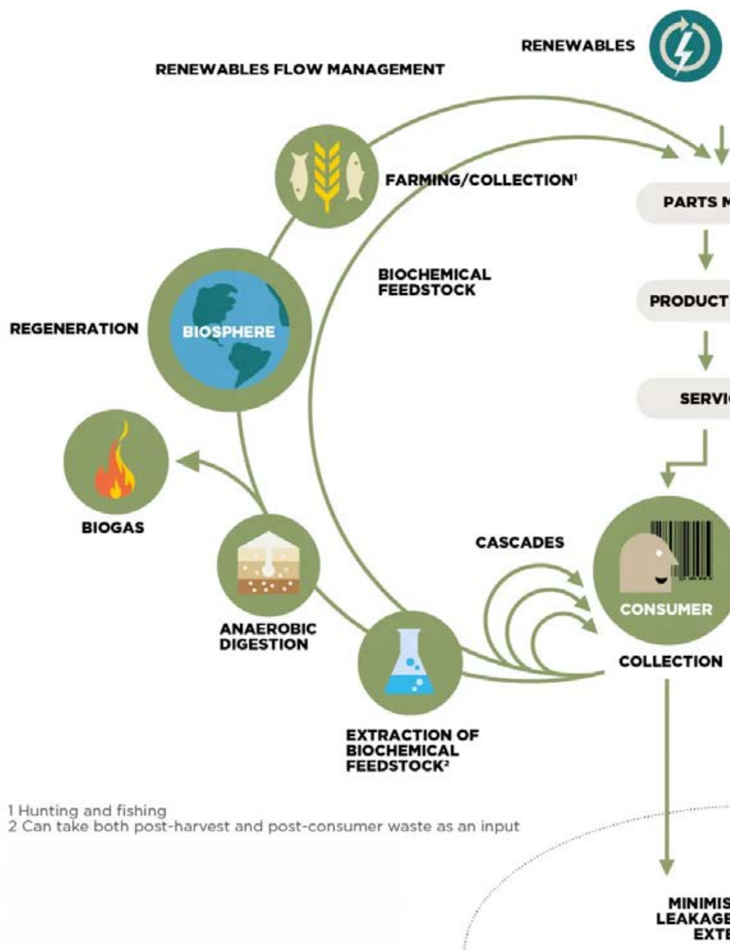
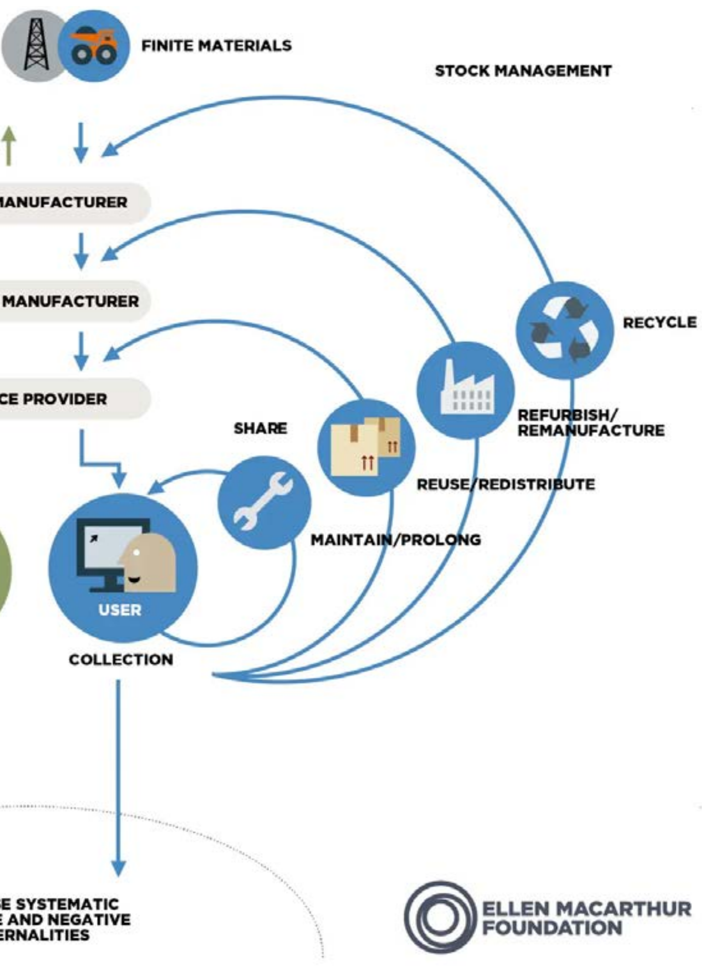


Fig. 9 Butterfly diagram, Ellen MacArthur Foundation

producing new items (Ellen MacArthur Foundation, n.d.).

1.4.9 Biological cycle

The core of the biological cycle is the concept of regeneration (The Biological Cycle of the Butterfly Diagram, 2022), the third principle of the previously mentioned circular economy.
This cycle predominantly involves consumable products, such as food and wood-based items (The Biological Cycle of the Butterfly Diagram, 2022).
These naturally renewable materials can be further valorized by cascading them into diverse value streams (The Biological Cycle of the Butterfly Diagram, 2022). In a circular economy, the concept of cascading refers to utilising the by-product of one process as the raw material for another one(Circular Economy and Cascading n.d.). For example, food by-products such as orange peel can be transformed into textiles (The Biological Cycle of the Butterfly Diagram, 2022). Alternatively, this could involve repurposing the material for simpler uses, like animal feed (The Biological Cycle of the Butterfly Diagram, 2022).



When organic materials have reached the end of their usability, they can be transformed through composting or anaerobic digestion to extract valuable nutrients (Circulate Products and Materials, n.d.). These processes allow for the recovery of essential nutrients such as nitrogen, phosphorus, potassium, and various micronutrients, which can then be used to renew the soil, increasing plant yield (Circulate Products and Materials, n.d.).

Bio-based biodegradable plastic products have the ability to be biodegraded or composted after their use, which helps to recover nutrients and contributes to the renewal of natural systems. This feature makes bio-based biodegradable plastics a great fit for the biological cycle, as it turns waste into a resource for new growth.

Moreover, bio-based plastic may offer another advantage compared to petroleum-based plastics. In the circular economy, the aim is to maintain the highest possible value of a product (Ellen MacArthur Foundation, n.d.). Thus, actions such as maintenance, repair, reuse, and remanufacturing are prioritised over recycling, especially in the technological cycle (Ritzen et al., 2023). The cycle of bio-based plastics differs from that of petroleum-based plastics (Ritzen et al., 2023). As bio-based plastics are derived from renewable resources, they do not emit CO_2

during their molecular decomposition processes, like incineration and biodegradation, unlike their petrochemical counterparts (Ritzen et al., 2023). This makes their molecular breakdown a circular loop (Ritzen et al., 2023).

1.4.10 Challenges and Strategies

Bio-based plastics alone do not entirely resolve the environmental challenges associated with plastic use and can still contribute to plastic pollution (Ritzen et al., 2023). Ensuring their sustainability and integration into a circular economy necessitates effective strategies for their end-of-life recovery (Ritzen et al., 2023).

Moreover, product design should always take into account how components can circulate within either the technical or biological cycles post-use (Circulate Products and Materials, n.d.). Currently, many products blend technical and biological materials in a manner that compromises their recyclability. For example, textiles combining natural and synthetic fibres can hinder the separation process required for recycling (Circulate Products and Materials, n.d.).

For products intended for the technical cycle, incorporating features that simplify repair, maintenance, or disassembly is advantageous (Circulate Products and Materials, n.d.). Conversely, when focusing on the biological cycle, as in the case of wooden furniture, it is important to ensure that biodegradable components like wood can be easily separated from non-biodegradable ones, such as screws (Circulate Products and Materials, n.d.). Additionally, the use of biodegradable adhesives or paints can further ensure that these products can be returned to the earth in alignment with the biological cycle's principles (Circulate Products and Materials, n.d.).

In conclusion, in the attempt to mitigate microplastic pollution from shoe soles through the use of bio-based, soil-biodegradable plastics, it is equally important to carefully consider strategies which can ensure a sustainable end-of-life disposal. This holds true, particularly for complex products, like shoes, which often utilize multiple materials. Ideally, some of these materials could be designed to be separated and enter the technical cycle for recycling, rather than ending up in landfills or being incinerated. Meanwhile, other components, such as the shoe sole, could be designed to enter the biological cycle, thus decomposing into nutrients.

1.5 Project Scope

This project aims at exploring the current range of bio-based, soil-biodegradable plastics available on the market and at determining their potential application in the redesign of a trail running shoe.

The goal is to design a shoe that does not release harmful microplastics into the environment from its outsole and to ensure an easy, sustainable end-of-life treatment for the product.

1.6 Project Approach and Methods

This research project follows the double diamond process and is divided into four phases. An exploratory approach is adopted, and different methods are applied in each phase.

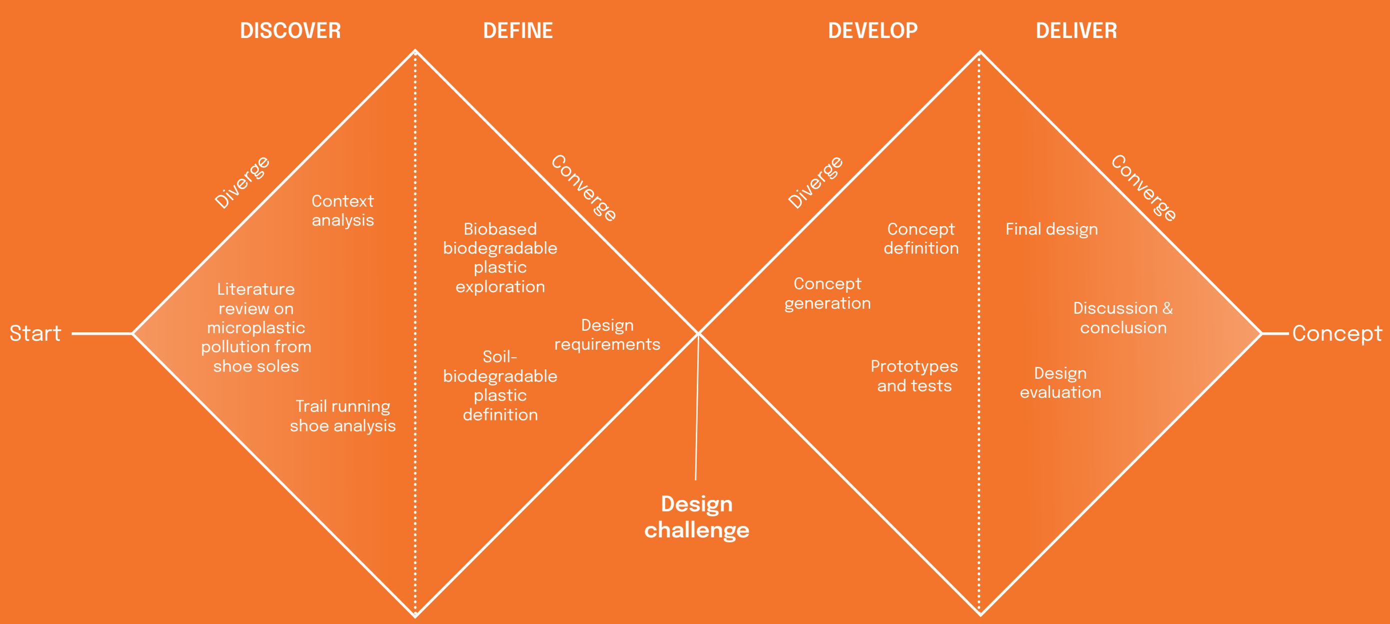
During the first phase, scientific papers were analyzed to understand the context of the project. This was followed by a product analysis to assess the functionality, usability, and durability of existing trail running shoes, focusing on the main components and materials commonly used.

Having gained an understanding of the context and the product, desk research was conducted to identify soil-biodegradable plastics with mechanical properties suitable for use as alternative materials for shoe outsoles. After narrowing down the options, a design challenge and a list of requirements were established to guide the design phase.

For the design phase, a morphological chart and design iterations through sketches and physical prototypes were used to achieve the final result.

Finally, the project was evaluated through critical analysis and conclusions, offering recommendations for future opportunities.

▶ Fig. 10 Structure and methodology followed in the design process



Discovery & Analysis

2 Context

The impact of microplastics from footwear, particularly from shoe sole abrasion, is an emerging environmental concern that has attracted considerable attention in recent research. This literature review synthesises findings from several studies investigating the presence and impact of microplastics in the environment, with a specific emphasis on those resulting from outdoor activities in natural areas.

The research for this review was conducted primarily on Researchgate and Google Scholar, utilising targeted keywords such as “microplastics pollution” and “shoe soles.” This filter helped narrow down the broad topic of microplastic pollution to gather data pertinent to the study. The review focuses on papers published in English and is based on the analysis of five significant research papers.

2.1 Related work

Recent research has identified shoe sole abrasion as a significant contributor to microplastic pollution, particularly in natural settings and high-foot-traffic areas (Cecchi, 2023; Forster et al., 2020). Similar to tyre wear, microplastic particles from shoe soles can be spread through wind and rainwater into both terrestrial and aquatic ecosystems, adversely affecting them (Cecchi, 2023).

Outdoor recreational activities, such as hiking and trail running, involve the use of various polymers and additives in clothing and footwear, making them notable sources of microplastics in natural environments (Forster et al., 2020). The types of plastics commonly found in footwear, including polyester, nylon fibres, ethylene vinyl acetate (EVA), Gore-tex, and different rubbers (e.g., carbon rubber, butyl rubber, styrene-butadiene rubber), present risks to wildlife and the food chain due to their chemical compositions (Forster et al., 2020; Cecchi, 2023).
Specifically, hiking boots and trail running shoes undergo considerable abrasion from ground friction, further adding to this pollution (Forster et al., 2020). Trail running shoes, designed with softer rubber outsole to enhance grip, exhibit a higher rate of wear (Sánchez, 2023), which may intensify the issue.

Fig. 11 Worn-out outsoles

Moreover, the increasing trend of participation in trail running events and the rapid growth in marathon participation underscores the potential for these activities to significantly boost microplastic release in natural areas over a short period (Forster et al., 2020; Forster, 2023). Specifically, from 2006 to 2017, the number of trail-running event participants in the USA rose by 4.6 million, and the hiking community expanded by approximately 15 million (Forster et al., 2020). Additionally, trail running competitions, which can draw hundreds to several thousand participants, often occur in remote wilderness areas where human activity is typically minimal (Forster et al., 2020).

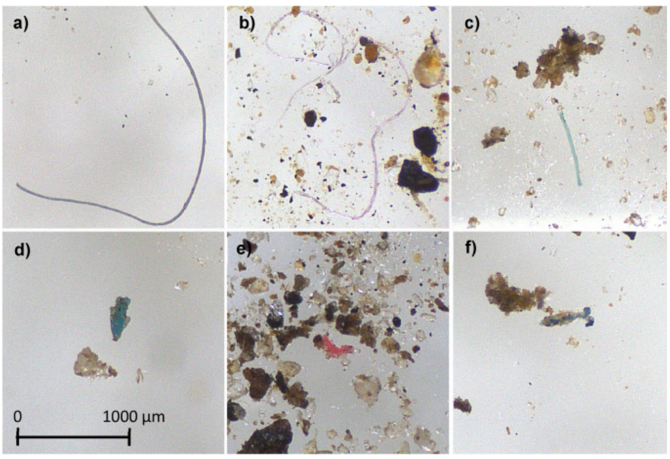
Consequently, the abrasion of footwear can readily release microplastics directly onto trail surfaces, impacting adjacent soil and vegetation (Forster, 2023). Further research in protected areas in Australia has documented the presence of microplastics on trail surfaces, highlighting outdoor recreation, especially trail running, as a significant source of pollution (Forster, 2023). Notably, in these areas, the dispersal of microplastics was more pronounced on inclines and rocky surfaces compared to flat terrain and soil (Forster, 2023). Additionally, the movement of these particles, propelled by rainfall and runoff, amplifies their distribution and impact on the environment (Forster, 2023). Thus, the use of sports shoes in outdoor activities can contribute to environmental stress and pollution, potentially affecting also areas far away from where sports are practised (Cecchi, 2023).

Microplastics from shoe soles contribute not only to the physical contamination of natural landscapes but also to the introduction of chemical pollutants into ecosystems (Cecchi, 2023; Lee et al., 2022). Research by Lee et al. (2022) and Kim et al. (2021) has examined the toxicity of microplastics derived from various types of shoes on soil health, plant growth, and freshwater organisms. These studies reveal that different shoes impose varying levels of environmental stress. For instance, sneakers adversely affect soil properties and inhibit plant growth, whereas running shoes might promote plant growth but can alter flavonoid content and affect photosynthetic factors (Lee et al., 2022). In aquatic environments, microplastics from both sneakers and running shoes have been shown to be particularly harmful, inhibiting algae growth and causing immobility and mortality in water fleas (Kim et al., 2021).

Overall, the long-term effects of microplastic pollution in natural settings are extensive and continue to be the subject of ongoing research. Microplastics can degrade soil quality by reducing water retention and disrupting nutrient cycles (Ghosh et al., 2023). In freshwater ecosystems, they pose threats to the food chain and aquatic life (Ghosh et al., 2023). There is also concern that microplastics could enter the human food chain, posing health risks to people consuming contaminated food or water (Ghosh et al., 2023). Given their small size and persistence, microplastics can readily accumulate in freshwater systems, making detection and removal challenging (Yee et al., 2021; Cecchi, 2023).

Addressing microplastic pollution from outdoor recreation requires a comprehensive approach that includes the development of more sustainable materials for outdoor equipment by manufacturers, policy implementation to control the impact of visitors in protected areas, and increasing awareness of environmental impacts

▶ Fig. 12 Visual microscopy of fibres (a-b-c) and rubber (d-e-f), (Forster et al., 2020)



among the public and outdoor enthusiasts (Cecchi, 2023; Forster et al., 2020).

In conclusion, this review reveals the need for further research and the development of sustainable materials for outdoor gear, especially trail running and hiking shoes, to reduce microplastic pollution in natural and protected environments. Investigating bio-based plastics with soil biodegradability properties is a promising step towards solving the microplastic issue by introducing materials that can decompose harmlessly in the environment.

Given their rapid wear and prevalent use in such environments, along with the rising number of running events in natural areas, trail running shoes have been selected as the product to redesign.

▶ Fig. 13 Ultramarathon running

2.2 Key findings

- Microplastic pollution from footwear, particularly shoe sole abrasion, is a growing environmental concern in natural areas.
- Outdoor recreational activities, such as trail running and hiking, contribute to harmful microplastic release due to the synthetic materials used in footwear.
- Increasing participation in trail running events and ultramarathons amplifies the potential for microplastic release in natural environments.
- These microplastics introduce chemical pollutants into the environment, impacting soil health, plant growth, and freshwater organisms.
- Addressing microplastic pollution from outdoor recreation requires a multifaceted approach involving sustainable material development, policy implementation, and raising awareness.

3 Product analysis

This chapter focuses on analysing trail running shoes to comprehend their standard construction, the main components, and the general lifespan. It also explores various strategies currently used in market products to reduce wear and tear.

The findings obtained from this analysis will be used in the next two phases: firstly, to identify a suitable material and, secondly, to explore how this product can be redesigned. The goal is to maintain its functional integrity while preventing the release of microplastics.

3.1 Trail running shoes

On average, the production of a standard pair of trail running shoes involves over 360 assembly steps and includes 65 different components (Footwear's (Carbon) Footprint, 2013). This complex process, which includes sewing, cutting, moulding, and heating various materials like plastics, fabrics, foams, and textiles, complicates recycling efforts. Consequently, most discarded shoes end up in landfills, where they can take decades to decompose, or they are incinerated, a process that releases harmful chemicals into the atmosphere and aggravates air pollution (Tonti, 2023; DiNapoli, 2024).

Yet, it is precisely the use of synthetic materials such as EVA foam, synthetic rubber, polyester, nylon, etc., chosen for their unique properties and used in specific components, that ensures trail running shoes meet the high standards of performance and comfort (Hanson & Hanson, 2023).

Despite their benefits, fragments from these materials, especially those generated by sole abrasion, contribute significantly to pollution. Market research indicates a gap in the availability of trail running shoes designed with microplastic pollution mitigation in mind.
However, in the world of running shoes, not strictly limited to trail running, innovative initiatives by brands such as ON and Adidas provide valuable insights for future designs.

3.2 Alternative approaches

ON has introduced a novel subscription model that allows customers to receive a new pair of running shoes every month for a fixed fee. When these shoes wear out, users can return them to the company, which ensures their responsible recycling. By adopting this subscription-based strategy, ON effectively collects materials that otherwise would not naturally decompose and are reused for the production of new shoes (ON, n.d.).

This approach could be adapted for the redesign of trail running shoes, particularly (if necessary) for parts that are not naturally biodegradable, by incorporating a service that facilitates the recovery of materials.

▶ Fig. 14 On Running Cyclon

Adidas's Futurecraft Loop project represents another innovative approach, producing a running shoe entirely from TPU (Thermoplastic Polyurethane), which is both 100% recycled and recyclable. To overcome the recycling challenges posed by glue, Adidas utilised laser technology to weld shoe components together, eliminating the need for toxic adhesives (Adidas, 2019).

In the context of redesigning trail running shoes, the approach of using a single material and minimising the reliance on glue is especially intriguing. The presence of glue can hinder the biodegradation or composting process unless the adhesive is completely natural and certified. Consequently, even if the outsole is made from soil-biodegradable plastics, potentially neutralising the harm of any released microplastics, biodegradation may not be a feasible end-of-life disposal method.

However, comprehending the primary components of these products is fundamental to identifying effective strategies for minimizing microplastic pollution from shoe soles and making disposal easier for end-users.

▶ Fig. 15 - 17 Adidas FutureCraft Loop

3.3 Main components

Trail running shoes consist of three main components: the upper part, the midsole, and the outsole.

3.3.1 The Upper Part

The upper part secures the foot, preventing excessive movement in various directions. It comprises several components, including overlays (synthetic materials for support), the heel counter (providing heel stability), the collar (foam padding for comfort and foot lockdown), and the toe box (the front section creating space for the toes) (Shoe Components, n.d.) .Two commonly used materials for the upper part are engineered mesh, prioritising breathability and lightness, and knit, known for its comfort and flexibility (Sánchez, 2023 - a).

3.3.2 The Midsole

The midsole is situated between the upper and the outsole and provides cushioning and controlling pronation. Midsoles come in various drop categories: zero drop (minimal cushioning), low drop (a midsole drop of 6mm or lower), and regular drop (midsole drop higher than 6mm) (Shoe Components, n.d.). These categories serve different running styles and preferences. Zero-drop offers a more natural feeling, while low-drop and regular-drop shoes provide varying levels of cushioning and support. Usually, midsoles are made in EVA foam or PU foam (Sánchez, 2023b).

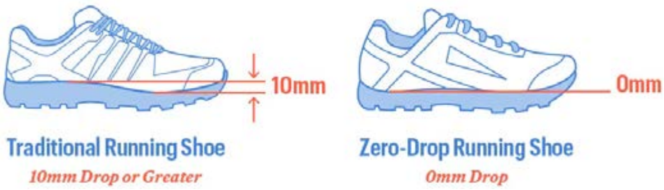


Fig. 18 Regular and zero drop midsole

3.3.3 The Outsole

The outsole, situated at the bottom of a shoe, plays a fundamental role in providing traction and determining the firmness, flexibility, and torsional

Fig. 19 Trail running shoe anatomy

rigidity of the shoe (Shoe Components, n.d.). Additionally, outsoles can come in various shapes, ranging from curved to straight. (Sánchez, 2023b)

Materials

Synthetic rubber is the predominant material used in running shoe outsoles due to its exceptional durability (Sánchez, 2023b). This synthetic rubber is created through a process called vulcanization, which involves the addition of sulphur to natural rubber, creating cross-links that harden the material and enhance its elasticity (TED-Ed, 2020). The outcome is a robust, yet elastic, material that offers excellent grip and long-lasting durability (TED-Ed, 2020).

Trail vs. Road Soles

The performance of a running shoe is significantly influenced by the grip and durability of its outsole (Sánchez, 2023b). Outsoles with superior grip are typically crafted from softer rubber, but they may wear out more quickly. Conversely, shoes designed for durability often feature harder rubber outsoles, sacrificing some grip (Sánchez, 2023b).

Trail running shoes are generally equipped with softer outsoles that provide enhanced grip, making them well-suited for tackling uneven and challenging terrains. In contrast, road running shoes are designed with harder outsoles that prioritise durability, making them particularly effective on flat asphalt pathways (Sánchez, 2023b).

Traction patterns

The lugs, or traction patterns, on an outsole are critical elements chosen based on the running surface (Sánchez, 2023b) These elements, defined by their depth, placement, and design, consist of rubber material that protrudes from the outsole. Shoes equipped with deep lugs, typically over 5mm, are optimal for running on technical trails (Store, n.d.).

For softer terrains such as grass or mud, larger lugs with greater spacing are effective in shedding mud and debris (Fig. 20). In contrast, uneven surfaces like sand or root-filled trails require lugs with varied angles and shapes, providing a multidirectional grip and reducing the risk of slips and falls (Fig. 21). On smoother terrains like gravel or dirt trails, shorter and simpler lugs offer greater flexibility and responsiveness (Sánchez, 2023) (Fig. 22).

▶ Fig. 20 Outsole for softer terrains

Fig. 21 Outsoles for trails and uneven surfaces ◀

▶ Fig. 22 Outsoles for gravel

3.4 Lifespan

The recommended lifespan of trail running shoes varies depending on usage. Manufacturers such as Nike and Asics suggest replacing shoes after 480 to 800 km, while Adidas recommends a switch after approximately 500 kilometres, varying by shoe model (Nike, a.d.; Asics, 2021; Adidas, 2023). The actual lifespan can be shorter or longer based on the user's characteristics and usage patterns.

The midsole, which absorbs the impact during running, often deteriorates first (Kuzma & CPT, 2021). On average, a runner takes 160 to 200 steps per minute, compressing the midsole foam. This continuous compression causes the foam to flatten and lose its shape, even in shoes that are not used regularly (Kuzma & CPT, 2021). A worn midsole reduces the shoe's ability to support the foot effectively, leading to overuse injuries in tendons and ligaments. (Kuzma & CPT, 2021)

The outsole also plays a significant role in the lifespan of the shoe. Similar to tyres, the outsole wears down with repeated impact, affecting the shoe's performance, increasing the risk of injury and releasing microplastic (Kuzma & CPT, 2021). This wear and tear also leaves the midsole more exposed and prone to damage and further microplastic pollution (Kuzma & CPT, 2021).

Other factors contributing to the need for replacement include the breakdown of the counter, which stabilises the foot and wear in the upper part of the shoe (Kuzma & CPT, 2021).

Moreover, the fabric of the upper part of the shoes may also develop holes or uneven wear patterns that can alter the shoe's fit, leading to unexpected problems over time. (Kuzma & CPT, 2021)

Fig. 23 Worn upper and interior parts ◀

Fig. 24 Midsole Compression ◀

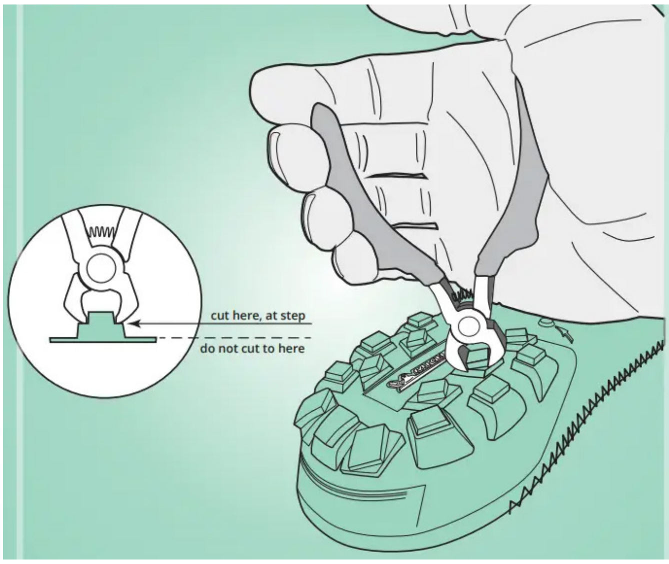
Fig. 25 Worn-out outsole ◀

3.5 Modularity in Trail Running Shoes

The traditional construction of trail running shoes typically prevents the replacement of deteriorated components. However, two notable projects in the trail running shoe industry currently stand out by providing customization options through easily accessible elements.

The Speedland SL:PDX, developed by Speedland, features a design that avoids the use of glue, facilitating disassembly and recycling at the product's end of life. The shoe incorporates a drop-in midsole (namely, a removable midsole) crafted from Pebax*, a material noted for its superior resilience and longer lifespan compared to traditional EVA foam (Speedland, n.d.; Randall, 2023). It also includes a removable carbon plate, an optional feature designed to enhance running efficiency and reactivity, positioned between the outsole and midsole. The outsole, made entirely of rubber by Michelin, is equipped with 6 mm lugs that users can trim to customize traction based on varying terrain conditions, although trimming is a permanent modification. Aimed at expert runners, the shoe is constructed from premium materials and is priced at $375 (Speedland, n.d.; Randall, 2023).

*Pebax® is a thermoplastic elastomer composed of polyamide and polyether backbone blocks. This speciality elastomer is characterized by its low material density, offering a broad spectrum of shore hardness values and exceptionally efficient energy return (Pebax® | Arkema Global, n.d.). A more sustainable version available is Pebax® Rnew®, a bio-based variant derived from castor beans (Bio-based Pebax® | Arkema Global, n.d.).



▶ Fig. 26 Speedland – Instructions on How to Trim the Lugs

▶ Fig. 27 Speedland SL:PDX

The design of this shoe incorporates a promising feature for runners, such as a removable midsole, typically the first component to show wear. However, the trimmable outsole, while innovative, may contribute to additional pollution. Despite this, the ability for customization by the end-user presents an intriguing aspect from a design perspective.

The second project, developed by the German startup Infinity Running, introduces running shoes with replaceable outsole elements (Infinity Running, n.d.). These shoes incorporate 10 modular elements within the sole, each designed to last up to 480 km, according to the company. They are available in different densities to suit various terrains: red for trail, black for road, and blue for street use, with green offering enhanced cushioning. This modularity caters not only to different terrains but also accommodates various foot types, adding a layer of customization to the footwear (Infinity Running, n.d.).

▶ Fig. 28 Infinity Running shoes, replaceable outsole elements

▶ Fig. 29 Infinity Running shoes

These projects present an alternative perspective on re-envisioning the product. By introducing updatable elements to address wear and tear, specifically focusing on the midsole and outsole, the components that deteriorate first with use, they offer an opportunity to enhance end-user accessibility. This approach represents an innovative strategy for such products.

3.6 Aesthetic

A common feature of running shoes, applicable to both road and trail scenarios, is the use of bright, vibrant colours. This choice typically serves multiple purposes: safety, psychological impact, and personal expression (Bartlett & Bartlett, 2023). For road running shoes, in particular, neon and reflective materials are employed to enhance visibility in low-light conditions, an essential safety measure to ensure runners are visible to drivers and pedestrians (Bartlett & Bartlett, 2023). Moreover, the colour of running shoes can influence emotions and performance, as different shades may evoke feelings of happiness, calmness, or energy, thereby impacting a runner's mood and motivation (Bartlett & Bartlett, 2023). Brands today increasingly use colour as a strategic marketing tool, with specific colours often emblematic of a brand's identity or the shoe's functional attributes (Bartlett & Bartlett, 2023).

While the market currently offers a wide variety of colour options, including softer shades for trail running shoes, the redesign phase presents an opportunity to explore how colour can communicate the project's commitment to sustainability.

Fig. 30 Trail running shoes ◀

3.7 Key findings

- On average, trail running shoes involve over 360 assembly steps and include 65 different components. The prevalent use of adhesives adds complexity to the recycling process.

- The synthetic material used provides good performance and comfort properties but contributes to the release of harmful microplastic.

- Nevertheless, despite several design strategies to reduce carbon footprint, there is a notable lack of shoes designed with microplastic mitigation in mind.

- Incorporating modularity and customization into shoe design, with a careful selection of materials, might be a viable strategy to enhance the durability of the product.

Exploration & Definition

4 Material Identification

After collecting relevant information and insights on the product, this chapter focuses on identifying bio-based, soil-biodegradable plastics with appropriate mechanical properties to meet the project's needs. Desk research was carried out to find such materials. Despite the current limitations in the market, two materials have been identified as the most promising for now, even if they are not ready to be used immediately. Based on the information gathered and looking at future possibilities, a design challenge and a list of requirements have been set up to guide the next phase.

4.1 Bio-based soil biodegradable plastic

Overall, markets for biodegradable plastics include agriculture & horticulture, paper coatings, adhesives, and additives (Ghosh & Jones, 2021). Narrowing down the research, several materials with suitable soil biodegradable characteristics were identified, such as PBS, Ceroflex, Ecovio, and NaturalFlex. These materials demonstrate remarkable biodegradability in soil and additionally offer home compostability.

BioPBS (Polybutylene succinate), sourced from natural materials such as sugarcane, cassava, and corn, is both soil biodegradable and home-compostable (BIOPBSTM | Mitsubishi Chemical Corporation, n.d.). Its primary use is in packaging applications, including flexible films and paper coatings. Coating paper with BioPBS, as opposed to non-biodegradable plastics, allows for compostability in both industrial and home settings (BIOPBSTM | Mitsubishi Chemical Corporation, n.d.).

Similar applications are seen with Ceroflex by Fkur, a starch-based plastic mainly used for plastic bags and mulch films (Biobased and Compostable Starch Compounds - FKuR, n.d.); Ecovio, a partially bio-based plastic employed for films in organic waste bags, shopping bags that also serve as organic waste bags, agricultural films, and various packaging solutions (EcoVio® (PBAT, PLA), n.d.); and NaturalFlex, a cellulose-based plastic designed for flexible packaging solutions (NatureFlex, 2020). These applications, however, are predominantly focused on food packaging and agriculture, limiting their adaptability for this project.

▶ Fig. 31 BioPBS packaging

▶ Fig. 32 Mulch films

Furthermore, brand owners currently prefer industrial compost environments for their ease of integration into organic waste management systems and effectiveness in plastic degradation (Ghosh & Jones, 2021). In terms effectiveness of microbial diversity and biodegradation rate the first one is industrial composting, then home composting, soil, freshwater, and lastly, marine environments (Ghosh & Jones, 2021). The number of certified products for each media type, as reported by Austria TUV, depicted in Fig.30, clearly illustrates this point.

Moreover, the item size and thickness significantly influence its biodegradability; thicker items require more time to disintegrate and decompose in the environment (Ghosh & Jones, 2021).

Additionally, the higher cost of alternative materials coupled with the underrecognized issue of microplastic pollution from shoe soles may hinder wider exploration by manufacturers.

Nowadays, there is a dominance of garden, agricultural, and horticultural products for soil biodegradable plastics and a preference for compostable plastics for packaging products (Ghosh & Jones, 2021).

However, the research highlighted two materials with potential: Terratek Flex, a partially bio-based elastomer, and PHA, a fully compostable plastic synthesized by bacteria.

Although Terratek Flex shows promise for the footwear industry, its soil biodegradability has not been explored. Meanwhile, PHA stands out for its biodegradability during use and at the end of life but is not yet deemed suitable for such applications. More information will be provided in the following chapter.

4.2 Terratek Flex GDH-B1

Terratek Flex GDH-B1 is a starch-based elastomer developed by Green Dot Bioplastics. This material, which is partially bio-based, and containing up to 35% biobased content, stands out as the first plastic elastomer that meets the standards for compostability in the industrial environment (Green Dot Bioplastics, 2022). According to the company, it also can biodegrade in home composting setups after several months.

This material is described as suitable for a wide range of plastic applications (injection moulding, profile extrusion, and extruded sheets) and finds its use in various products such as packaging, footwear, automotive accessories, and children's toys (Green Dot Bioplastics, 2022).
Despite the material's promising features, there

▶ Fig. 33 Certified products in different biotypes according to TÜV Austria, (Ghosh & Jones, 2021)

	No. finished products	No. raw materials	Main constituents	Maximum thickness
Industrial compostable	1463	496	PLA, PHAs, PBS, PBAT, Thermoplastic starch, Regenerated Cellulose, Cellulose Acetate	3.3 mm
Home compostable	739	187	PBAT, Thermoplastic starch, PHAs, Regenerated Cellulose, Cellulose Acetate	1.1 mm
Soil	23	52	PHAs, Thermoplastic starch, Regenerated Cellulose, Cellulose Acetate	Not required[a]
Water	1	20	Regenerated Cellulose, Cellulose Acetate, PHAs	5 mm
Marine	0	20	Thermoplastic starch, PHAs	N/A

[a]TÜV Austria does not impose any disintegration criteria for soil biodegradable products.

is a notable absence of detailed information available online. This lack of data and limited examples of existing products utilising this material hinder a comprehensive evaluation. Additionally, the claims regarding its home compostability are not entirely transparent on the website, further complicating an accurate assessment and suitability for the project scope.

Although the soil biodegradability of Terratek Flex has not been studied, it has the potential to be home-compostable at the end of its lifecycle, which offers a more sustainable option than synthetic rubber. However, as previously discussed, its use could still contribute to microplastic pollution. Therefore, despite its suitable mechanical properties, it cannot be used for the project's goal.

4.3 PHA

PHA, or Polyhydroxyalkanoates, is a biodegradable plastic, which is extremely promising for its versatility and sustainability compared to the current bio-based alternatives. PHA can be produced by different bacteria, but also yeasts and plants, when genetically modified for this purpose (Molenveld et al., 2020). PHA encompasses nine distinct product families, including some commercially available types like PHB, PHBV, and PHBH (Acharjee et al., 2022). These materials exhibit different properties ranging from elastomers-like features to highly crystalline polymers, based on their chemical structure (Molenveld et al., 2020).
Products made from PHA are 100% compostable and biodegradable, capable of breaking down harmlessly in soil or marine environments without adversely affecting nature (GO!PHA; Molenveld et al., 2020). This plastic can be composted at home, in industrial settings, or biodegraded in anaerobic digestion facilities. Common processing techniques for PHA include injection moulding, sheet extrusion, and thermoforming (Molenveld et al., 2020).

Currently, PHAs find extensive use in various industrial applications. These include the medical sector (biomedicine), agriculture, packaging, and food-related products such as cutlery, cups, straws, and coffee capsules. PHA is also used in manufacturing 3D printer filaments (Poltronieri & Kumar, 2019; GO!PHA).

▶ Fig. 34 Degradation test of plastic and wooden forks over nine weeks at a compost site (Plastics, 2021)

▶ Fig. 35 PHA bottle biodegradation (Yousuf, 2018)

In the context of this project, a particular type of PHA with elastomer-like properties was considered.

However, it was only available as a 3D printing filament spool. This filament was acquired during this part of the project to evaluate its properties and possible applications (Fig.38-39). This led to several observations. First, the shore (hardness) of the filament was not adequately soft for components like soles or outsoles. Secondly, the layering process in FDM (Fused Deposition Modeling) 3D printing may have compromised the product's flexibility and its evaluation in comparison to existing flexible materials. Finally, the project's focus was not related to 3D-printed footwear.
Consequently, PHA was not suitable to be selected for further testing in this project, despite its intriguing properties.

Fig. 36 3D printed PHA by ColorFabb ◀

Fig. 37 PHA 3D filament by ColorFabb ◀

▶ Fig. 38-39 PHA print tests conducted during the exploration phase

4.4 Conclusion and Design Challenge

The analysis conducted reveals that, despite promising forecasts, the current primary applications of soil biodegradable plastics are predominantly in food packaging and agricultural films. This is also observed in the labelling system, which is essentially focused on this category of products. While the two materials identified for this project, PHA and Terratek Flex, appear to be suitable on paper, practical challenges emerge in their actual use and in conducting physical tests to assess feasibility.

Moreover, the analysis revealed that the challenge is not only limited to the research of the material but also in the design of the product and in its final assembly. Currently, according to this research, there is no definitive proof of a material that is fully suitable to be used for trail running shoe soles to mitigate microplastic pollution in the environment. Nonetheless, this opens up the possibility to conceptualise and ideate a design for such a trail shoe.

Despite a few modular examples on the market, which have a potentially longer lifespan, trail running shoes are currently designed to follow a linear economy. This issue could be mitigated through the use of biodegradable and compostable materials and the application of circular design strategies.
Based on the insights acquired from the analysis of the product, a design challenge emerges:

4.5 Design requirements

To guide the design process, a list of design requirements was established, based on the findings from the research phase. These requirements are categorized into demands, criteria the product must meet, and wishes, criteria the product should meet in the redesign proposal.

1) The product must prevent the release of harmful microplastics from the shoe sole.

2) The product must be designed for proper end-of-life disposal, facilitating its integration into biological and/or technical cycles.

3) The product must eliminate the necessity of toxic adhesives

4) The overall product should have a lifespan higher than 600 km* of running

5)The product should aim to reduce the number of components at least by 50%* without compromising its functionality

6)The product aesthetic should communicate to the end user its transparency in sustainability distinguishing it from the average trail running shoes

* Average number of components: 65
* Average trail running shoe lifespan

"How can the design of trail running shoes be rethought to address wear and tear sustainably, specifically targeting the reduction of microplastic release?"

Ideation & Development

5 Design Phase

This chapter provides an overview of the design phase, beginning with product research. A morphological chart is utilized to aid the ideation process, visually presenting various concepts through sketches. After selecting the concept that aligns with the established design requirements and feasibility criteria, a prototype development session is initiated.

The prototype development session progresses through various iterations, documenting the journey from the initial idea to the final design, step by step. The chapter concludes with the presentation of the proposed concept, BioStep.

5.1 Trail running shoes overview

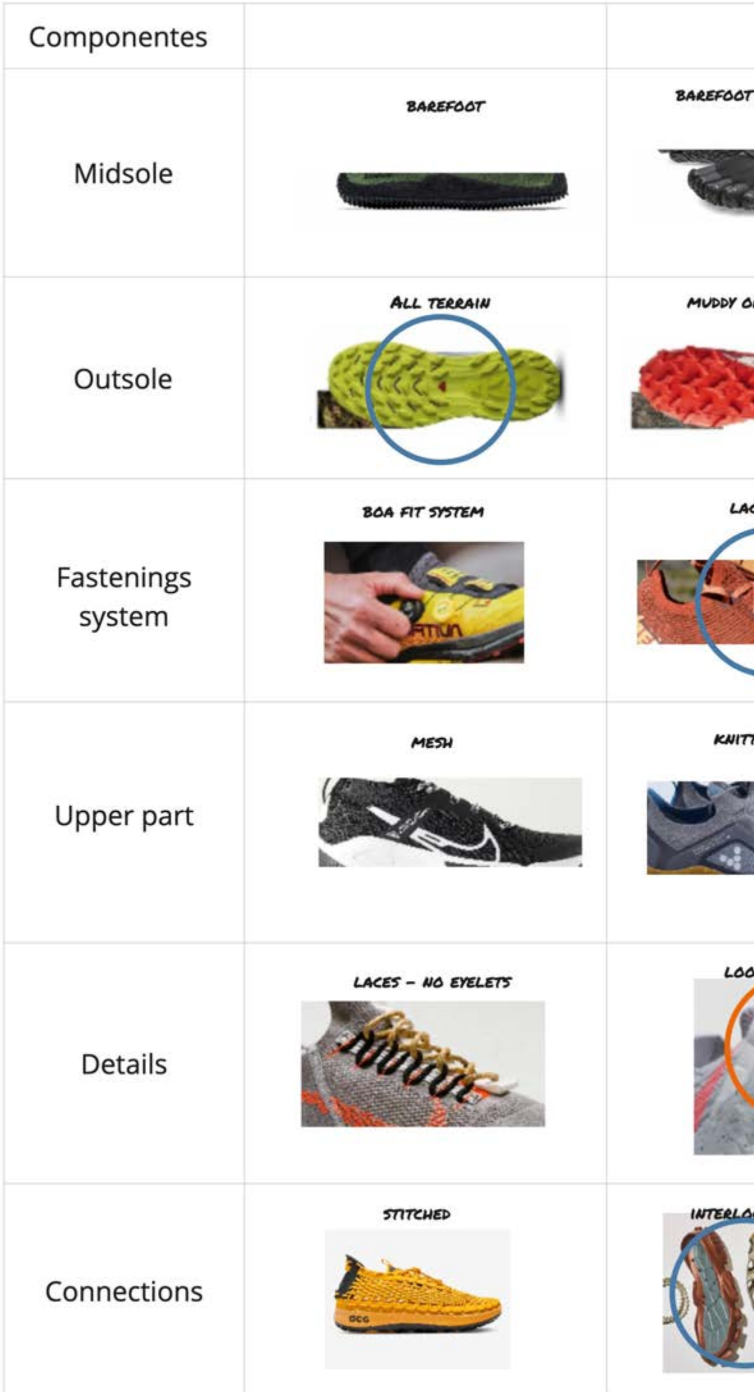
Before the application of the morphological chart, an examination of various trail running shoes available in the market was conducted. This included a review of the most popular models and brands such as Nike, Merrel, and Adidas. Additionally, the use of eco-friendly materials was considered. For example, Allbirds employs a combination of eucalyptus tree fibre and merino wool for the upper portion and natural rubber for the outsole. The CMF (colours, materials, and finishes) of these shoes were also examined for inspiration. This initial review of diverse products was essential in collecting options for the morphological chart. Highlighted below are the most notable examples identified during the review, which will provide inspiration for the redesign phase.

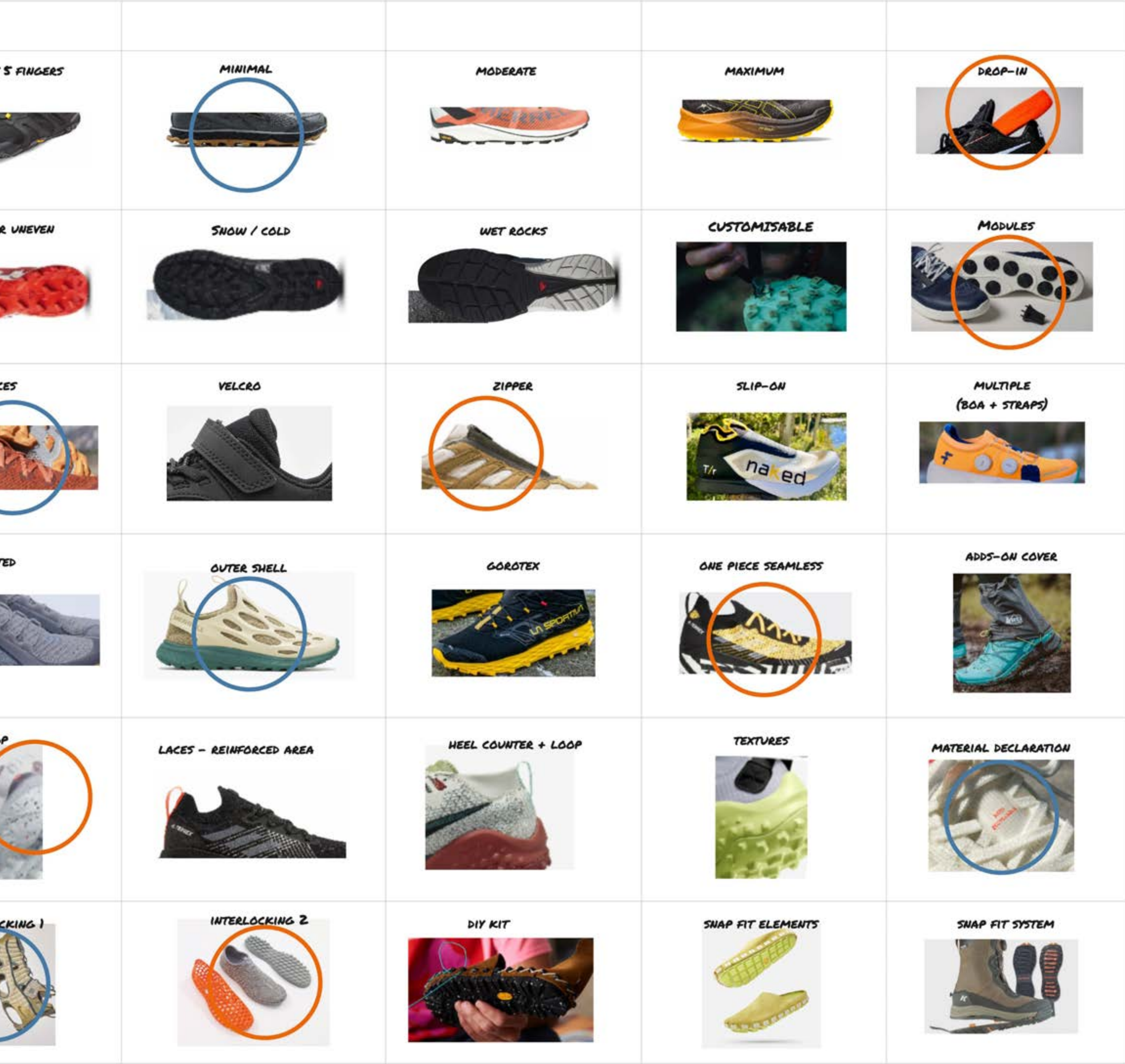
Fig. 40 Trail running shoes moodboard

5.2 Morphological chart

To kick-start the ideation process, a morphological chart was utilized. Shoes, being complex products with numerous variations in the market, each aim to meet similar functional requirements through different features.
To effectively navigate this complexity, a morphological chart is employed. This tool provides a general overview of the main components of a trail running shoe, showcasing the different possibilities for achieving similar functionality.
The final row of the chart, dedicated to exploring alternative methods for joining components without glue, involved reviewing a wide range of footwear to gather broader inspiration.

Based on the solutions marked in the chart, two potential design concepts were sketched.




5 FINGERS
MINIMAL
MODERATE
MAXIMUM
DROP-IN
UNEVEN
SNOW / COLD
WET ROCKS
CUSTOMISABLE
MODULES
VELCRO
ZIPPER
SLIP-ON
MULTIPLE
(BOA + STRAPS)
OUTER SHELL
GOROTEX
ONE PIECE SEAMLESS
ADDS-ON COVER
LACES - REINFORCED AREA
HEEL COUNTER + LOOP
TEXTURES
MATERIAL DECLARATION
INTERLOCKING 2
DIY KIT
SNAP FIT ELEMENTS
SNAP FIT SYSTEM

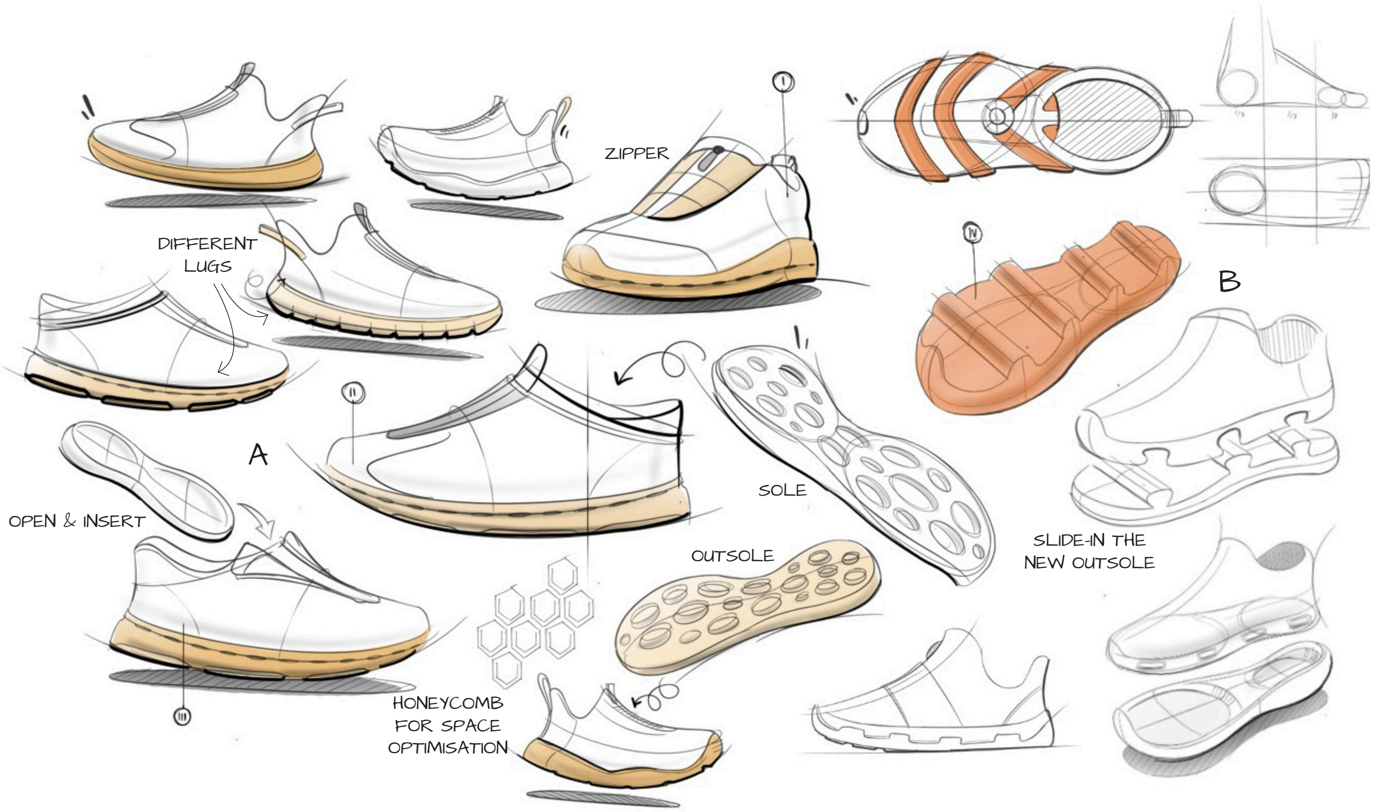
5.3.1 Direction one

This concept, based on the orange selections on the morphological chart, introduces a modular design that allows users to easily replace the outsole, typically one of the first components to exhibit wear. This feature reduces the need to replace entire shoes due to outsole deterioration.

The proposed system enables the simple exchange of the worn outsole, thereby extending the shoe's useful life. Utilizing soil-biodegradable plastics, such as PHA, for the outsole facilitates an environmentally friendly disposal process. These materials can be broken down in soil or composted at home, turning a used outsole into beneficial nutrients for the earth.

To eliminate the use of glue, two replacement mechanisms are proposed. The first is an interlocking system (A) that ensures a secure fit between the outsole and the sole. The second is a sliding mechanism (B) designed for easy outsole alignment, although it may encounter resistance due to rubber friction. Both designs allow for the interchangeability of outsoles to suit different terrain conditions.

The shoe's upper part incorporates a zipper system to simplify the insertion of the outsole. This concept is extended to the midsole with a "drop-in" system, reflecting a preference for removable components. This modularity not only enhances the shoe's longevity but can also simplify component recycling for the end user.



5.3.2 Direction two

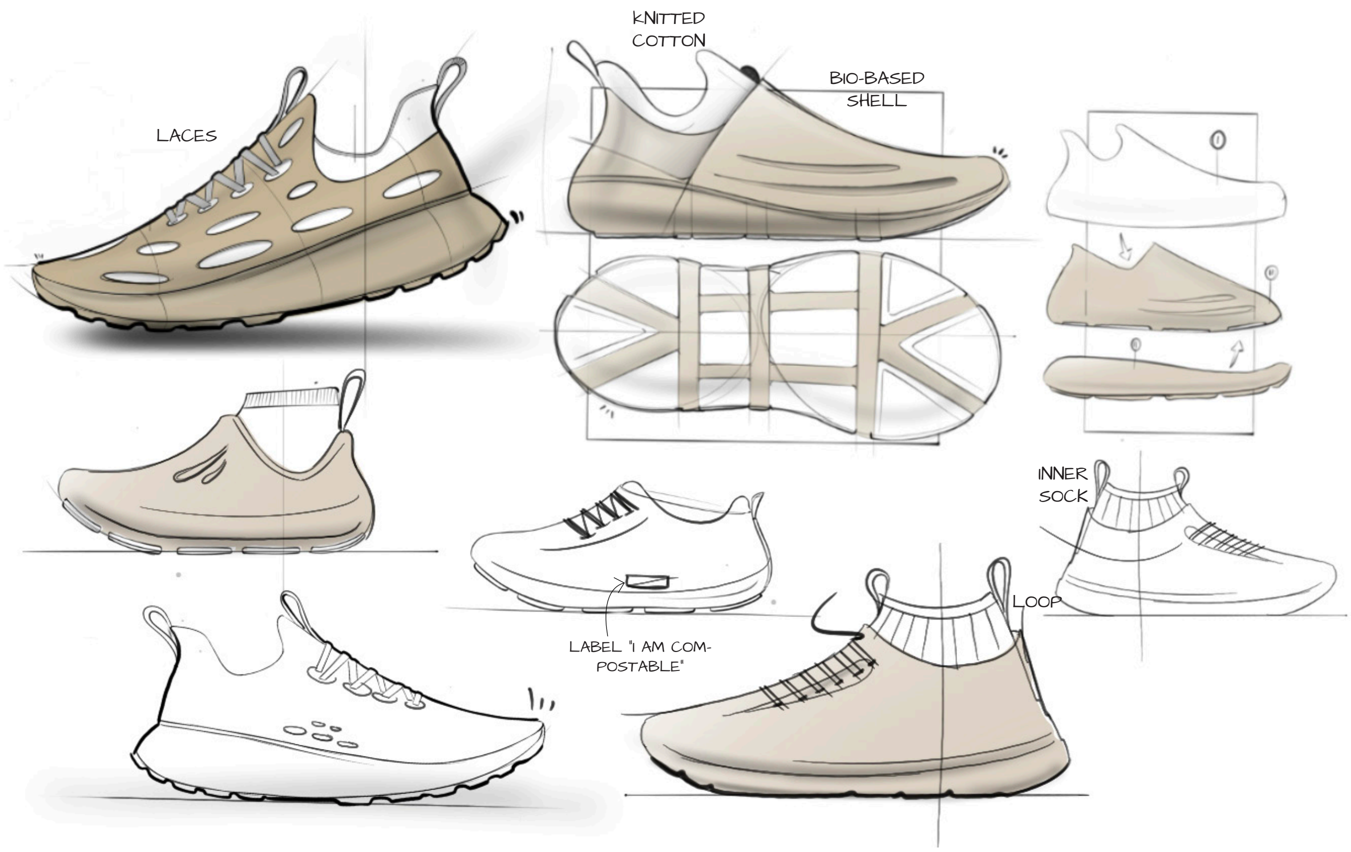
The second direction is based on the choices marked in blue on the morphological chart.

This idea presents an alternative approach where soil-biodegradable plastic serves as the primary material for the shoe, not only for the outsole, significantly reducing the number of components. The idea involves creating a fully biodegradable outer shell paired with an inner sock designed to enhance foot comfort and breathability.
The outsole's tread could be designed for versatility across various terrains, while the upper part might incorporate laces for a tight fit.

In addition, a small loop in the inner sock could simplify foot insertion. This concept also considers a drop-in system for the outsole, enhancing end-of-life disposal options. The outer shell could feature a small label detailing the material's nature and advantages.

At the end of its lifecycle, the product can be buried without harming the soil or, depending on its properties, may even be suitable for home composting. The inner sock could be made from natural fibres like cotton or exploring fabrics derived from orange peels or food by-products to make a product that fits the biological cycle in the circular economy.

However, while this solution promises enhanced circularity with fewer components, considerations such as the outer shell's weight and comfort need careful evaluation. Material properties might make the shell too stiff, limiting movement for running.



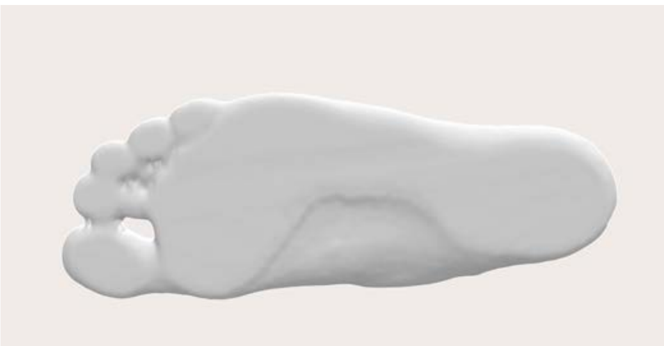
5.4 Design process and Exploration

To explore the two directions and select the most promising idea, a series of simple prototypes were made.

The lower part of the shoe, including both the sole and the outsole, was first examined through smaller-scale prototypes. This initial exploration was followed by the development of a 3D model to comprehensively study the system. Utilizing 3D printing and rapid prototyping techniques, the first feasibility of these components was evaluated. A 3D-scanned model of a foot served as a reference throughout this process, ensuring the accuracy of the shoe's volume and overall proportions.

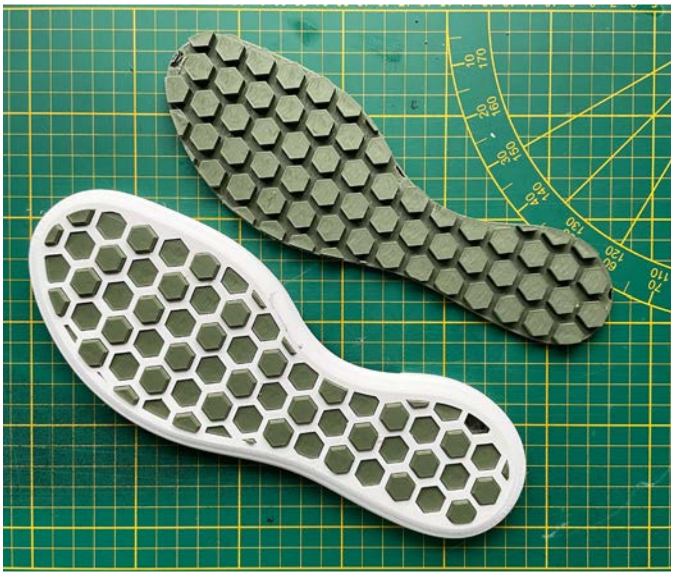
The development of the upper part of the shoe focused on fabric construction, exploring various patterns by studying different designs. Before advancing to full-scale prototyping, smaller-scale models were employed to explore and understand the possibilities through tangible examples.

▶ Fig. 41-42 3D scanned foot



▶ Fig. 43-44 First iterations and small prototypes

▶ Fig. 45 Honeycomb interlocking system exploration



5.5 Concept definition

Although both concepts meet the established requirements and propose alternatives to traditional design, the first concept aligns more closely with a conventional running shoe, whereas the second presents a more unconventional approach. The decision to proceed with the first concept over the second was not based on a formal evaluation method of the concepts' potential but rather on practical considerations related to material properties and design feasibility.

The second concept, though very intriguing from a sustainable perspective, posed practical challenges for immediate implementation. Its reliance on an outer shell raised concerns about potential restrictions on movement, a critical factor for running shoes. Additionally, the absence of similar designs in the market also implied that pursuing this direction might be too ambitious, given the current market readiness and project timeline.

Therefore, the decision was made to advance with the first concept. This choice represents a balance between durability and sustainability, achievable within a realistic timeframe. The selected concept aims to design footwear that not only avoids the release of harmful microplastics but also presents an environmentally friendly end-of-life option beyond landfilling or incineration. This approach seeks to balance performance needs with environmental responsibility, offering a viable solution that can be explored within the available project duration.

6 Concept development

This section describes the prototype development process. It is structured in two main stages leading to the final concept. The process begins with the making of a low-fidelity prototype, focusing on the basic design and functional elements. Following this, a more detailed version is developed. Both stages were essential in progressing, allowing for gradual improvements and iterations based on feedback and testing.

6.1 Low fi prototype

The primary aim of this low-fidelity prototype is to bring the conceptual design into a tangible form. Its purpose is to assess the overall feasibility, explore the potential for eliminating the use of adhesives across all components, evaluate the space requirements for the interlocking system, and ensure proper fit for the foot. The prototype has been constructed in a size 37.

While the choice of materials was not the central focus at this stage, the prototype was sufficiently developed to allow for an evaluation of the concept. The introduction of a zipper system enabled an almost fully openable design, proving to be effective in facilitating the replacement of the outsole and midsole.

The connection between the upper part (green) and the sole (yellow) is achieved using a blanket stitch technique. This assembly method could be further refined by designing a specific stitching area on the sole. Additional enhancements could strengthen the heel counter and toe area of the upper part, ensuring greater durability and support.

6.2 Intermediate prototype

The second prototype is developed to evaluate the interlocking system designed for the replaceable outsole and select a suitable material for the upper part that offers a realistic texture and feel. In this iteration, the 3D-printed components are made in PHA (polyhydroxyalkanoates) and TPU (thermoplastic polyurethane).

While PHA was initially considered due to its biodegradable properties, it was inappropriate for further development because of its unsuitable shore value. Consequently, PHA was not utilized in the next stages.

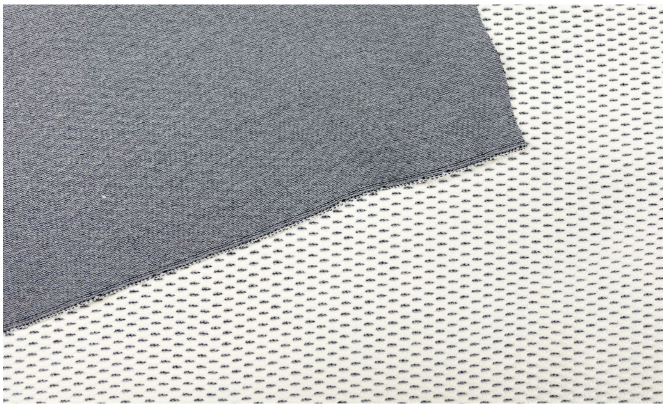
The description of this prototype will start with the upper part, detailing the material choices and design considerations, and will conclude with an examination of the outsole, focusing on the functionality and integration of the interlocking mechanism.

6.2.1 Upper part 

The objective for the upper part was to identify a material that would simplify the design process while preserving an authentic look and feel. Conventionally, additional padding is incorporated into the upper part for comfort, which typically requires extra materials and increased labour. The challenge was to find a material that could

▶ Fig. 46 Fabric selection at the textile company replicate the visual and tactile characteristics of 3D knitted cotton, something soft and thick enough to ensure comfort without complicating the design. Following discussions with a textile manufacturer in Italy, a Jordan WX fabric, a fibre consisting of wool and nylon was selected for its close approximation to the desired texture and its comfort factor.

While a semi-synthetic fibre should not be the ultimate choice for the final product due to its material composition and the challenge of being recycled, it was considered suitable for the purposes of this prototype only, owing to its visual and tactile qualities.

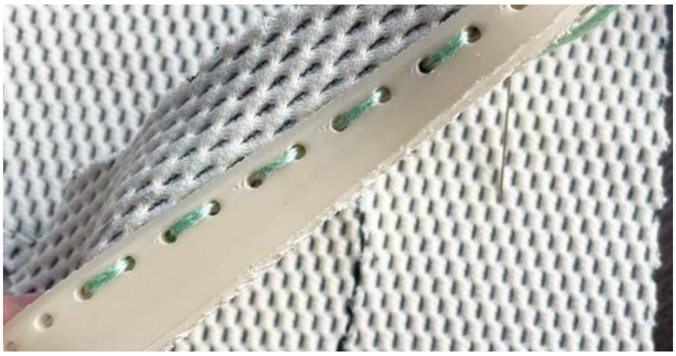


▶ Fig. 47 Jordan WX fabric

6.2.2 Stitching

In this prototype, various stitching techniques were explored to enhance the attachment between the upper part and the sole, eliminating the need for glue as specified in the design requirements. Additionally, the positioning of the yarn on the sole was strategically designed to simplify the assembly process.

To determine the most durable and secure stitching method that could replace the use of glue, three different stitch types were evaluated. The double-thread stitch proved to be the most efficient and was consequently chosen.



▶ Fig. 48 Double thread stitch

▶ Fig. 49 Single thread stitch

▶ Fig. 50 Diagonal stitch

6.2.3 Fastening system

The fastening system, incorporating a zipper, has been refined for improved functionality. The zipper is attached to the upper part of the shoe, offering a broad opening to facilitate the insertion of the outsole and, possibly, a “drop-in” midsole. In this prototype, the midsole is constructed from a foam material to replicate its bulk and to assess the fit for the foot comprehensively. Meanwhile, the outsole is printed in TPU.

▶ Fig. 51-52 Shoe, midsole (black) and outsole (white)

6.2.4 Reinforcement

Additional enhancements have been made to the design of the upper part, especially in the area around the ankle's topline. A tongue has been incorporated to alleviate discomfort between the ankle and the zipper during wear. Furthermore, a loop has been introduced on the backside to achieve a better fit. Both the loop and the tongue serve dual functions; they not only improve comfort but also strengthen the shoe's structure,

▶ Fig. 53 Loop and tongue

particularly at the toe box and heel counter, by adding a double layer of materials at these critical points.

6.2.5 Overall fit

Given the project's emphasis on distinct primary goals, a detailed ergonomic study was not conducted. Nevertheless, each prototype was tested with a single user to evaluate the performance of its various components. The fit was considered generally satisfactory; however, the PHA material used for the sole was identified as overly rigid, suggesting that a softer material might enhance comfort. The zipper proved to be efficient in securing the foot, implying that additional fastening systems may not be necessary at this stage. It is important to note, however, that thus far, the product has been tested solely for walking and not yet for running.

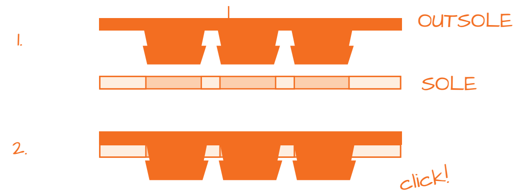
6.2.6 Outsole & Interlocking system

To replace the outsole once it is worn out, a mechanism has been designed and tested to simplify this process. The concept involves using the sole as a container into which the outsole is inserted. The lugs on the outsole, which contact the ground, protrude a few millimetres from the sole to provide traction. The outsole is designed to be easily pushed into place. Three different outsole patterns were explored.

The first iteration (1), overly dense and printed with a rigid material, proved less effective and needed refinement.
The second pattern (2), printed in TPU to better mimic elastomer properties, showed more promising results. Despite this improvement, further modifications were necessary to enhance its functionality. An additional snap-fit or click system might be required to secure the outsole in place, especially for use on uneven terrains. Given the concept's focus on replacing only the outsole while keeping the sole attached to the upper part for a longer duration, it was crucial to ensure the sole's durability against wear and tear. Thus, the areas in contact with the ground were minimized.

In the third iteration (3), instead of a single pattern across the entire outsole, further analysis was conducted on current outsoles and foot pressure points. As a result, the area was divided into five main zones to improve comfort and usability. Moreover, a snap-fit system was added to ensure that the outsole would be in place during usage.

Continuing to refine, the fourth iteration adjusted the outsole's size, leading to an optimized design where only a minimal portion of the sole makes ground contact, thus potentially extending its durability on different terrains.



▶ Fig. 54 Outsoles evolution

▶ Fig. 55 Interlocking system between outsole and sole

▶ Fig. 56-59 Instructions on how to replace the outsole

BioStep

Step Softly on the Earth

BioStep is the final concept for a trail running shoe, focused on reducing harmful microplastics using bio-based soil biodegradable plastics and promoting a sustainable approach to its end-of-life cycle.

This section offers a thorough explanation of the product features and its lifecycle.

7 Key features and overview

The final design of "BioStep" consists of four key elements, an upper part made from knitted fabric (A), a removable midsole (B), a replaceable outsole (C), and a sole (D) that is stitched together with the upper part.

As previously mentioned, given the current absence of readily available materials that meet the necessary criteria, with PHA being the closest yet not fully suitable, the focus has shifted towards the product's architecture. "BioStep" conceptualizes how a trail running shoe could be redesigned once an appropriate material becomes available.

The outsole is made of bio-based, soil-degradable plastic. It features an interlocking system to facilitate easy removal. Worn outsoles can be effortlessly replaced and disposed of in soil or compost, in line with the material's biodegradable nature.

The sole, also made from bio-based, biodegradable plastic, is stiffer than the material used for the outsole. It is stitched to the upper part and designed to last longer, thereby increasing the overall lifespan of the shoe.

The midsole incorporates a glue-free "drop-in" system, allowing users to replace it as needed. The use of bio-based materials, such as Pebax Rnew® derived from castor oil, may represent an advancement for future scenarios.

The upper part is crafted from knitted fabric, aiming to use natural fibres such as eucalyptus, hemp, cotton, or wool, ensuring ease of integration into technical or biological cycles at the end of life.

The overall aesthetic of the product, characterized by softer, lighter colours, sets it apart from the vibrant and bold hues commonly found in trail running shoes. This design decision aims to underscore the value of sustainability to consumers. Bright colours are exclusively used on the tread, making the product easily identifiable.

7.1 Customisable outsoles

The "BioStep" outsole is designed for replacement not only due to wear and tear but also to adapt the gear to different terrain conditions. This versatility enables customization for a wide range of landscapes, based on the user's needs.

For example, the outsole (a) is designed for smoother terrains like gravel or dirt paths, featuring shorter and simpler lugs for optimal performance. Conversely, the alternative outsole (b) is designed with lugs that are spaced further apart, making it better suited for softer terrains such as grass, where enhanced grip is necessary.

▶ Fig. 60-61 Gravel and grass trail paths

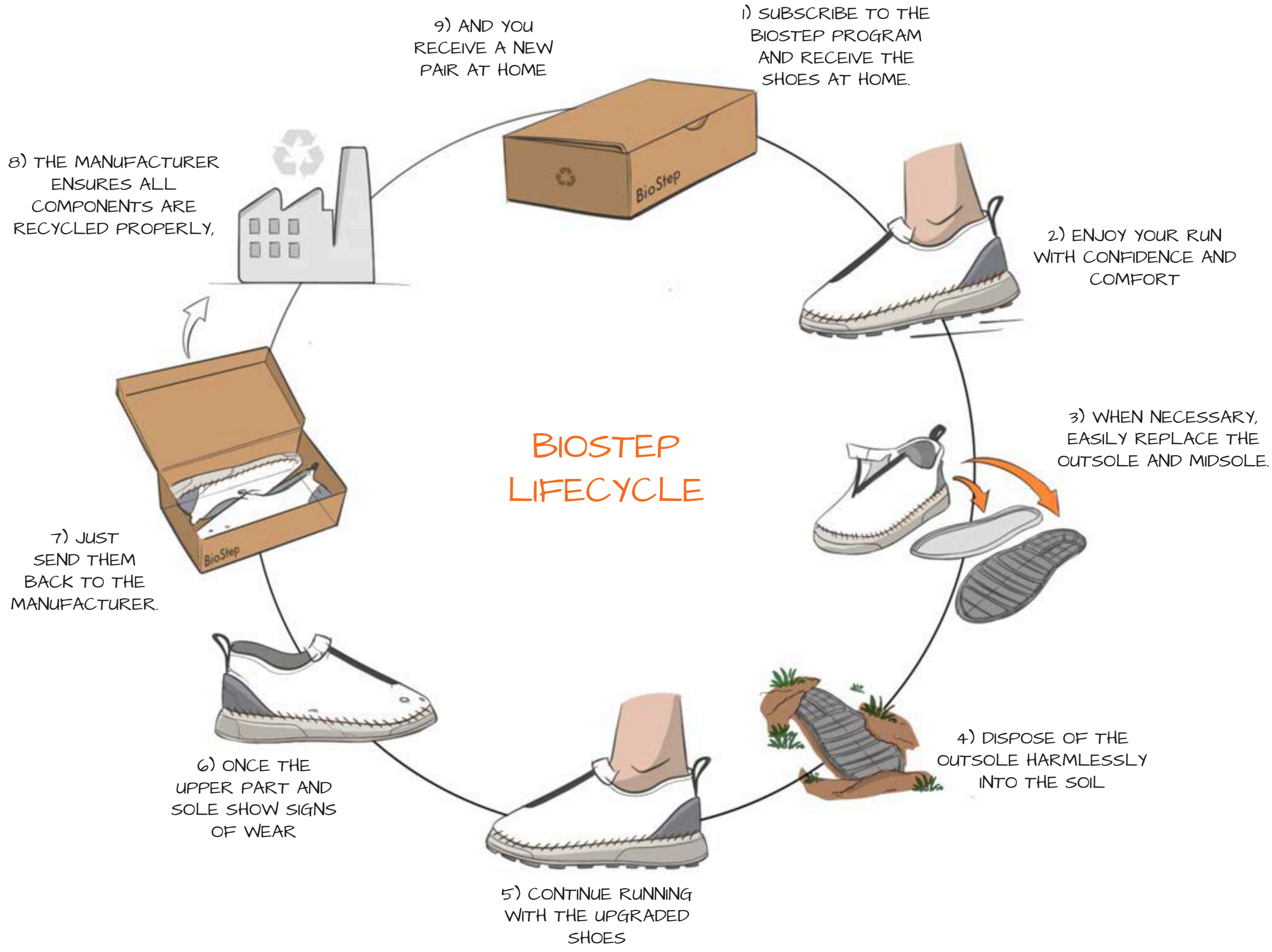
▶ Fig. 62 Outsole insertion

▶ Fig. 63 Midsole insertion

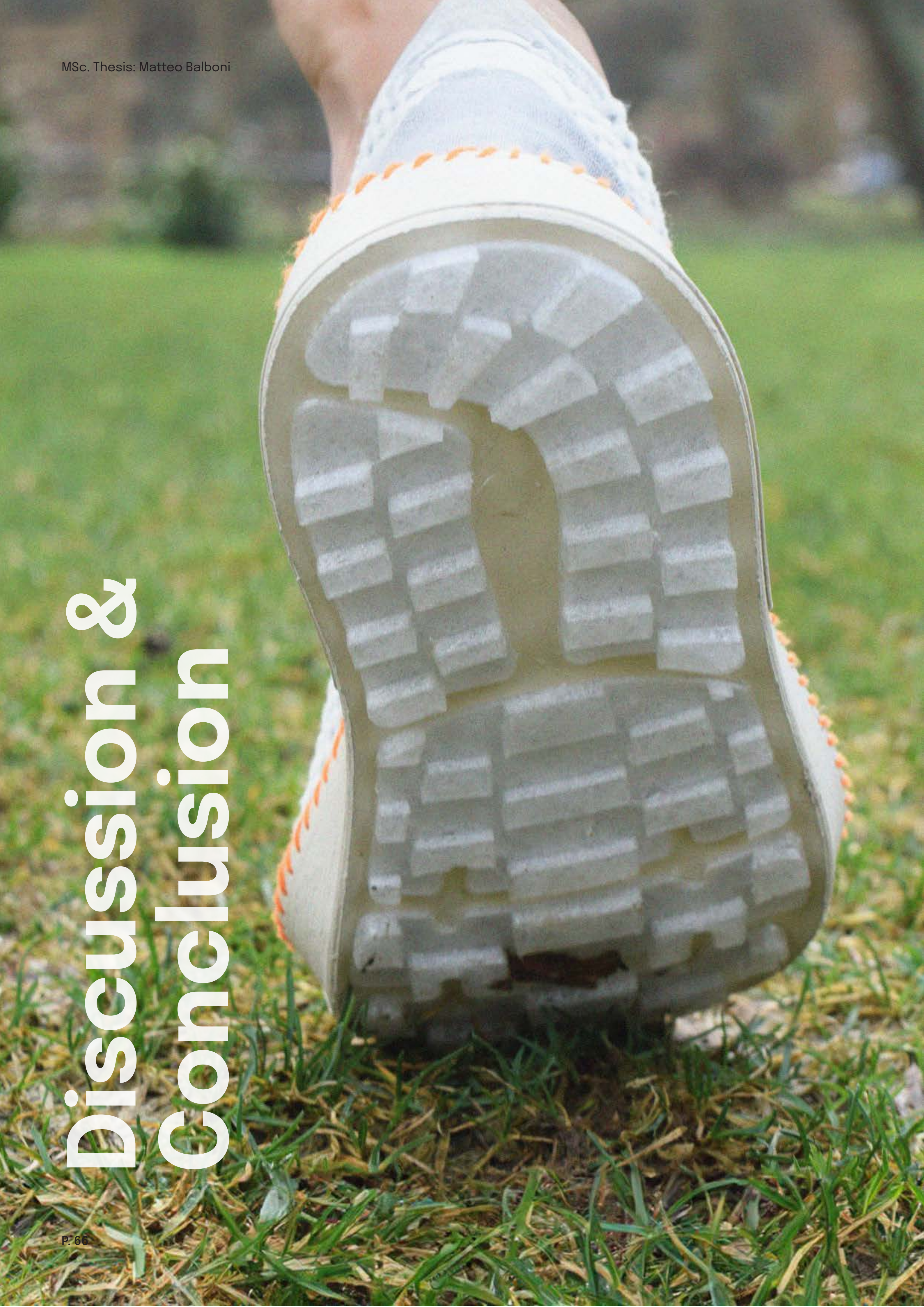
7.2 Product Lifecycle

The product lifecycle is designed to minimize the environmental impact of the product both during use and at its end of life. As the outsole begins to show wear, it can be conveniently replaced and disposed of harmlessly in soil. This approach enables the preservation of the rest of the shoe, extending the overall lifespan of the footwear.

When it becomes necessary to replace both the sole and the upper part, users can return them to the manufacturer for recycling, receiving a new pair in return through a subscription program. This strategy aims to establish a sustainable cycle, ensuring that even non-biodegradable components are properly collected and recycled by the manufacturer.



Discussion & Conclusion



8 Discussion & Conclusion

This section explores the project's evaluation, where the concept is critically analyzed component by component, highlighting potential directions for future enhancements. The aim is to delineate the next steps required for further development.

8.1 Evaluating BioStep: challenges and future directions

This project aimed to investigate the use of (soil) biodegradable plastics in trail running shoes to prevent the spread of harmful microplastics during use. Additionally, the project sought to understand how this material could affect the overall design of a shoe, which is typically designed with a linear lifespan.
No material on the market met the necessary criteria of flexibility, resistance and biodegradability, preventing the possibility to conduct performance tests. Consequently, a few assumptions were made, including the use of a hypothetical rubber-like material with soil biodegradability features. The analysis and research conducted on the product highlighted design opportunities, which were explored through the prototype sessions.

The following paragraphs discuss and critically evaluate each part of the product. The product has been tested for walking and further work is needed to evaluate its performance when running on uneven surfaces. For further development of the product, data and feedback on usability and durability will be collected and implemented.

8.1.1 The outsole

The effectiveness of the replacement system for the outsole requires more tests to fully understand its functionality, particularly the performance during usage. Furthermore, the interlocking mechanism needs additional refinement and testing during running scenarios. In future developments, the system should be watertight, an important feature considering the weather conditions encountered in trail running.

The use of soil-biodegradable plastic for the outsole might lead to quicker wear and tear compared to synthetic rubber, potentially reducing the product's longevity. However, it may open up new business opportunities. For example, the outsoles could be sold in bulks, similar to pen refills or printer ink cartridges.

Moreover, another opportunity relies on the opportunity to wear the same shoe and only change the outsoles, according to different terrain conditions. This will require further testing to assess outsole performance and reliability.

Identifying a suitable material is an important step that would facilitate more targeted testing. Beyond the mechanical properties, the environmental impact, specifically in terms of microplastic pollution and soil biodegradability, deserves a focused investigation. It is essential to study how these biodegradable materials behave in soil health over time to prevent any harmful effects on the environment.

8.1.2 The midsole

The midsole was analysed and recognized as the first component of wear and tear in traditional trail running shoes. Consequently, the entire shoe needs to be replaced, especially in professional settings.
The concept of a drop-in midsole introduces several benefits. Firstly, it facilitates the recycling of individual parts since it is not permanently bonded to the shoe, making separation easier. Secondly, it offers the flexibility to customize firmness according to the user's preferences by choosing different foam densities.
This modular approach has been gaining popularity and appears to be a promising strategy for redesigning footwear with an emphasis on enhancing recyclability. The bio-based material used by the company Speedland, Pebax Renew could be a valuable option for the future.

8.1.3 The upper part

The exploration of the upper part occurred primarily in the step of prototyping. Therefore, extensive research for identifying suitable and sustainable fibres is essential for future improvements.
In general, the ideal material should be versatile enough to handle and resist various weather and soil conditions, such as mud or rain, where the fabric becomes easily wet and dirty. Moreover, it is fundamental to find a fabric which is easy to clean, as the upper part is intended to be kept for an extended period.

Furthermore, the stitching technique used to attach the upper part to the sole requires also extensive testing to assess its functionality. Examples in the market, like Speedland shoes, which make use of the same technique, indicate the potential for a reliable system.

Finally, further research on shoe comfort is necessary, particularly with the aim of minimizing the number of components and materials used. However, this approach requires careful consideration to ensure that reductions do not compromise the footwear's overall comfort and performance.

8.1.4 The sole

The material currently selected for the sole is a bio-based, biodegradable plastic. It could potentially be the same as the outsole but stiffer, given it needs to last longer and offer better resistance to abrasion, especially in those areas in contact with the ground. Consequently, future research to identify a suitable material would be beneficial. Such an assessment is crucial to establish the frequency of replacement needed. In the "BioStep" concept, this component is meant to be returned to the company for composting, likely in industrial facilities to speed up the degradation process. However, with an appropriate material selection, this scenario could be different, offering for instance home compostability or soil biodegradability.

8.1.5 Ergonomics

A detailed ergonomic study is necessary to improve the overall product design. During the prototype session, the product was tested with a single participant. The insights obtained were useful for improving the overall fit throughout the development of different prototypes, leading to modifications in the fastening system, sole size and materials.
Further and extensive tests with more participants will help in collecting useful feedback for refining the design and obtaining a comprehensive assessment of the shoe's ergonomics.

8.1.6 Materials and Prototypes

The prototypes were developed using an FDM printer with TPU material for the final version. Consequently, the overall flexibility and usability were inherently limited by the selected materials and the manufacturing process. Future investigations with alternative materials and different manufacturing techniques could help with the development of the final product. Another aspect which deserves further consideration is the weight of the product, as it can directly affect the running performance.
Thus, this analysis can be considered as a starting point for exploring replaceable elements using bio-based biodegradable plastics.

8.1.7 User Perception

It is important to conduct research to understand the perceptions of users and to gain insights into different aspects, such as a subscription for having a pair of shoes, and the possibility to replace the outsole, thus updating the product while keeping some components for a longer time.

Therefore, in order to further develop the product, it may be useful to collect data and feedback from potential users, namely trail runners.

8.2 Conclusion

This research project investigates the issue of microplastic pollution released from shoe soles, focusing on trail running shoes in natural environments. Such pollution directly harms ecosystems, impacting microorganisms, soil, and water bodies. An exploration to identify readily usable, suitable materials revealed that, currently, no soil-biodegradable plastic available can reduce microplastic pollution while offering the same performance characteristics as synthetic rubber for shoe soles. PHA emerges as the most promising material, due to its semi-flexible properties, yet it currently lacks the necessary flexibility for such applications. Additionally, PHA is only available in its "raw" form as a 3D printing filament. While there are several promising materials with biodegradable properties on the market, their applications are primarily limited to plastic mulch films and food packaging and they lack the necessary resistance for this application. Moreover, another limiting factor consists in the higher cost of bio-based plastic compared to petroleum-based plastics, and in the fact that microplastic pollution from shoe soles is an overlooked issue. Lastly, the thickness of the biodegradable material plays an important role in the necessary timeframe for its decomposition.

The outcome of this project is an analysis which assesses different current issues of trail running shoes. First of all, the microplastic release in the environment, second the short lifespan due to wear and tear which leads to a full replacement of the entire shoe. Last, the fact that generally, the shoes are designed using multiple materials glued together, hinders the recycling process. Hence, the product ends up in landfills or incinerators.

This led to the development of a concept proposal aimed at addressing these issues. The concept takes into account the potential of bio-based biodegradable plastic to prevent harmful microplastic pollution in the environment. Moreover, it explores alternative ways to enhance the product's lifespan, by taking into consideration modularity and upgradability.

The final outcome is "BioStep" a first prototype for alternative trail running shoes. Although tests in running scenarios are still to be performed, BioStep represents a starting point for the development of more sustainable footwear. Finally, there is an urgent need for more worldwide awareness of microplastic pollution, especially among trail runners; at the same time, both manufacturers, designers and final users would benefit from a closer collaboration during the ideation and development of new products.

8.3 Reflection

I decided to work on this project for several reasons. Primarily, I felt a duty as a designer to reconsider the environmental impact of products and explore opportunities for redesigning them. The challenge presented by this project immediately resonated with me as the right direction to work on.

Additionally, during the internship before my graduation, I participated in a redesign process session, where there was interest in utilising bio-based plastics for a new product. I remember there was common confusion among designers regarding terms like “bioplastic”, “bio-based biodegradable”, and “compostable”, and how to properly select them. Therefore, this episode further motivated me to explore this area when I read about this graduation project opportunity.

In the initial phase, the absence of a specific material for testing posed several challenges to me. Despite several attempts to contact companies developing suitable materials, I did not receive any response, leading to some confusion early on. The goal of reducing microplastics was clear, yet designing a shoe without detailed material knowledge was challenging for me. Ideally, I would have preferred to focus on a single material to better understand its possibilities and limitations, exploring the project with tangible solutions, rather than imagining a future suitable material.

Organising the project into distinct phases was very helpful. A good starting point to start facing these challenges was to initially focus on the context and the product analysis, in order to understand the current problems of trail running shoes as a source of microplastic pollution. The analysis was crucial to formulate many ideas.

I feel that my skills as a designer were exploited in the design phase and during ideas generation, sketching, and prototype development. However, I recognize the need for a more efficient design process to avoid unnecessary work and accelerate task fulfilment. Despite this, I am generally satisfied with the outcome, though more strategic planning could have facilitated a few phases, such as product testing.

One of my biggest challenges was documenting the research phase comprehensively yet concisely, ensuring that the report contained all the relevant information. Thankfully, ChatGPT was valuable in refining my writing, helping to articulate concepts more professionally. However, the tool was used only as writing assistance, and not for researching relevant information about the context. Instead, this was conducted through databases like ResearchGate and Google Scholar. Additional information and articles were searched on Google.

This project concludes my academic career, and I am glad to have addressed such a significant topic for my final assignment. My passion for rethinking everyday products to minimise their environmental impact remains strong, and my future career will undoubtedly benefit from the knowledge I have gained in this project.

References

- *Acharjee, S. A., Bharali, P., Gogoi, B., Sorhie, V., Walling, B., & Alemtoshi. (2022). PHA-Based Bioplastic: a Potential Alternative to Address Microplastic Pollution. Water, Air, & Soil Pollution, 234(1). https://doi.org/10.1007/s11270-022-06029-2*

- *Adidas - Shoe Tracking - (2023) https://help.runtastic.com/hc/en-us/articles/209585209-Shoe-Tracking*

- *Adidas unlocks a circular future for Sports with Futurecraft.loop: a performance running shoe made to be remade. (2019, April 17). Adidas News Site | Press Resources for All Brands, Sports and Innovations. https://news.adidas.com/running/adidas-unlocks-a-circular-future-for-sports-with-futurecraft.loop--a-performance-running-shoe-made-t/s/c2c22316-0c3e-4e7b-8c32-408ad3178865*

- *Al-Khairy, D., Fu, W., Alzahmi, A., Twizere, J., Amin, S. A., Salehi- Ashtiani, K., & Mystikou, A. (2022). Closing the Gap between Bio-Based and Petroleum-Based Plastic through Bioengineering. Microorganisms, 10(12), 2320. https://doi.org/10.3390/microorganisms10122320*

- *Alaerts, L., Augustinus, M., & Van Acker, K. (2018). Impact of Bio-Based plastics on current recycling of plastics. Sustainability, 10(5), 1487. https://doi.org/10.3390/su10051487*

- *Asics. (2021, November 12). Here's how to know when to replace your running shoes. ASICS Blog. https://www.asics.com/za/en-za/blog/article/when-to-replace-your-running-shoes*

- *Balena Science. (n.d.). Balena. Designed for circularity. https://balena.science/*

- *Bartlett, J., & Bartlett, J. (2023, December 4). Why are running shoes so bright and colorful (And what do different colors mean?). Your Next Run. https://yournext.run/why-are-running-shoes-so-bright-and-colorful/*

Biobased and compostable starch compounds - FKuR (EN). (n.d.). https://fkur.com/en/bioplastics/ceroflex/

- *Biodegradable Polymer "BIOPBSTM" | Products | Mitsubishi Chemical Corporation. (n.d.). Mitsubishi Chemical Corporation. https://www.m-chemical.co.jp/en/products/departments/mcc/sustainable/product/1201025_7964.html*

- *BLUEVIEW | Sustainable shoes & Biodegradable footwear. (n.d.). https://blueviewfootwear.com/*

- *Briassoulis, D., & Innocenti, F. D. (2017). Standards for soil biodegradable plastics. In Green chemistry and sustainable technology (pp. 139–168). https://doi.org/10.1007/978-3-662-54130-2_6*

- *Bocken, N., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. ResearchGate. https://www.researchgate.net/publication/309699661_Product_design_and_business_model_strategies_for_a_circular_economy*

- *Cecchi, P. (2023). Plastics on the rocks: the* *invisible but harmful footprint of shoe soles. Comptes Rendus Geoscience, 355(G1), 135–144. https://doi.org/10.5802/crgeos.199*

- *Circular economy introduction. (n.d.). https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview*
- *Circulate products and materials. (n.d.). https://www.ellenmacarthurfoundation.org/circulate-products-and-materials*
- *Di Bartolo, A., Infurna, G., & Dintcheva, N. T. (2021). A review of bioplastics and their adoption in the circular economy. Polymers, 13(8), 1229. https://doi.org/10.3390/polym13081229*
- *DiNapoli, T. (2024, February 10). Global Shoe Waste: The environmental impact of Footwear. Unsustainable. https://www.unsustainablemagazine.com/global-shoe-waste/#*
- *EcoVio® (PBAT, PLA). (n.d.). https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html*
- *Ellen Macarthur, circular economy. (n.d.). https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview*
- *European Bioplastic (2021). Biodegradable plastics do not cause persistent microplastics. European Bioplastics e.V. https://www.european-bioplastics.org/biodegradable-plastics-do-not-cause-persistent-microplastics/*
- *European Bioplastics e.V. https://www.european-bioplastics.org/faq-items/what-are-the-required-circumstances-for-a-compostable-product-to-compost/*
- *European Bioplastics. (2023). Bioplastics - Industry standards & labels.*
- *European Bioplastics. (n.d.- a). Bioplastics. European Bioplastics e.V. https://www.european-bioplastics.org/bioplastics/*
- *European Bioplastics. (n.d.-b). What are the required circumstances for a compostable product to compost?*
- *European Bioplastics. (n.d.-c). Labels. European Bioplastics e.V. https://www.european-bioplastics.org/bioplastics/standards/labels/*
- *European Bioplastics. (n.d.-d). Market. European Bioplastics e.V. https://www.european-bioplastics.org/market/*
- *European Bioplastics. (n.d.-e). Market. European Bioplastics e.V. https://www.european-bioplastics.org/market/*
- *European Commission, Biobased, biodegradable and compostable plastics. (2023, January 11). Environment. https://environment.ec.europa.eu/topics/plastics/biobased-biodegradable-and-compostable-plastics_en*
- *European Environmental Agency, Biodegradable and compostable plastics — challenges and opportunities. (n.d.). European Environment*

Agency. https://www.eea.europa.eu/publications/biodegradable-and-compostable-plastics

- *EuroPlas. (2023, September 18). How much does biodegradable plastic cost? EuroPlas. https://europlas.com.vn/en-US/blog-1/how-much-does-biodegradable-plastic-cost*

- *Federation, B. P. (n.d.). Packaging Waste directive & Compostable packaging. British Plastics Federation. https://www.bpf.co.uk/topics/Standards_for_compostability.aspx#:~:text=Home%20compostable%20packaging%20and%20plastics,be%20deemed%20%27home%20compostable%27.*

- *Footwear's (carbon) footprint. (2013, May 22). MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2013/footwear-carbon-footprint-0522*

- *For ever®. (n.d.). For Ever® - Bio. https://www.forever.pt/en/advanced_sustainable_solutions/thermoplastic_2/thermoplastic_bio*

- *Forster, N. A. (2023, October 26). An Examination of Microplastic Pollution in Protected Areas from Outdoor Recreation. Research UNE. https://rune.une.edu.au/web/handle/1959.11/56510*

- *Forster, N., Tighe, M., & Wilson, S. C. (2020). Microplastics in soils of wilderness areas: What is the significance of outdoor clothing and footwear? Geoderma, 378, 114612. https://doi.org/10.1016/j.geoderma.2020.114612*

- *GO!PHA. (2019). White paper #3: PHA's the natural materials of the future - preventing plastics pollution with PHA. Retrieved from https://static1.squarespace.com/static/5fb2575cf94ec942fe192fb3/t/5fbf6ae79b1ed03538d37d90/1606380264322/GO%21PHA+white+paper+%233+-+PHA%27s+the+natural+materials+of+the+future+-+preventing+plastics+pollution+with+PHA+-+September+2019.pdf*

  Ghosh, K., & Jones, B. H. (2021). Roadmap to Biodegradable Plastics—Current state and research needs. ACS Sustainable Chemistry & Engineering, 9(18), 6170–6187. https://doi.org/10.1021/acssuschemeng.1c00801

- *Green Dot Bioplastics. (2022, December 16). Elastomers - Green Dot Bioplastics. https://www.greendotbioplastics.com/materials/elastomer/*

- *Guliyev, V., Tanunchai, B., Udovenko, M., Menyailo, O. V., Glaser, B., Purahong, W., Buscot, F., & Blagodatskaya, E. (2023). Degradation of Bio-Based and Biodegradable plastic and its contribution to soil organic carbon stock. Polymers, 15(3), 660. https://doi.org/10.3390/polym15030660*

- *Hamzelou, J. (2023, June 1). Microplastics are everywhere. What does that mean for our immune systems? MIT Technology Review. https://www.technologyreview.com/2023/06/02/1073822/microplastics-immune-systems/*

- *Hanson, M., & Hanson, M. (2023, February 14). Running Shoes are Part of an Environmental Crisis. Is Change Coming? Trail Runner Magazine. https://www.trailrunnermag.com/people/*

culture-people/running-shoes-are-part-of-an-environmental-crisis-is-change-coming/

- *Infinite Running. (n.d.). Infinite Running - Sportschuhe aus deutscher Produktion. https://infinite-running.com/*
- *Kim, L., Kim, D., Kim, S. A., Kim, H., Lee, T., & An, Y. (2022). Are your shoes safe for the environment? – Toxicity screening of leachates from microplastic fragments of shoe soles using freshwater organisms. Journal of Hazardous Materials, 421, 126779. https://doi.org/10.1016/j.jhazmat.2021.126779*
- *Knight, C. (2023, August 9). What is the linear economy? European Investment Bank. https://www.eib.org/en/stories/linear-economy-recycling*
- *Kuzma, C., & CPT, C. S. (2021, October 27). How often to replace running shoes—and 3 signs that show it's time to get a new pair. SELF. https://www.self.com/story/how-often-to-replace-running-shoes*
- *Lai, Y., Dong, L., Li, Q., Li, P., & Liu, J. (2021). Sampling of micro- and nano-plastics in environmental matrixes. TrAC Trends in Analytical Chemistry, 145, 116461. https://doi.org/10.1016/j.trac.2021.116461*
- *Lassen, C., Hansen, S. F., Magnusson, K., Hartmann, N. B., Rehne Jensen, P., Nielsen, T. G., & Brinch, A. (2015). Microplastics: Occurrence, effects and sources of releases to the environment in Denmark. Danish Environmental Protection Agency. http://mst.dk/service/publikationer/publikationsarkiv/2015/nov/rapport-ommikroplast*
- *Lee, T., Kim, L., Kim, D., An, S. H., & An, Y. (2022). Microplastics from shoe sole fragments cause oxidative stress in a plant (Vigna radiata) and impair soil environment. Journal of Hazardous Materials, 429, 128306. https://doi.org/10.1016/j.jhazmat.2022.128306*
- *Michael Carus, Lara Dammer, Dr. Ángel Puente, Achim Raschka, Dr. Oliver Arendt, (2017). RoadToBio_Drop-in paper*
- *Molenveld, K., Bos, H., & Van Der Spa, M. (2020). Biobased Plastics 2020. https://doi.org/10.18174/534587*
- *Muthu, S. S., & Li, Y. (2021). The environmental impact of footwear and footwear materials. In Elsevier eBooks (pp. 305–320). https://doi.org/10.1016/b978-0-12-821606-4.00015-6*
- *NatureFlex. (2020, January 8). Compostable Product Packaging by NatureFlexTM. https://www.natureflex.com/uk/*
- *Nike - How often should I replace my running shoes? (n.d.). Nike.com. https://www.nike.com/nl/en/a/how-often-to-replace-running-shoes*
- *Oakes, K. (2022, February 24). Why biodegradables won't solve the plastic crisis. BBC Future. https://www.bbc.com/future/article/20191030-why-biodegradables-wont-solve-the-plastic-crisis*

- *OK biodegradable soil. (n.d.). Labelinfo. https://www.labelinfo.be/label/ok-biodegradable-soil*

- *OK biodegradable water. (n.d.). Labelinfo. https://www.labelinfo.be/label/ok-biodegradable-water*

- *on. (n.d.-b). https://www.on-running.com/en-nl/collection/cyclon*

- *Plastics and the circular economy. (n.d.). https://www.ellenmacarthurfoundation.org/plastics-and-the-circular-economy-deep-dive*

- *Pebax® Elastomers Family | Arkema Global. (n.d.). https://www.arkema.com/global/en/products/product-finder/product-range/technicalpolymers/pebax-product-family/*

- *Plastics Europe. (2022, February 11). Microplastics • Plastics Europe. https://plasticseurope.org/sustainability/plastics-health/microplastics/*

- *Poltronieri, P., & Kumar, P. (2019). Polyhydroxyalkanoates (PHAs) in industrial applications. In Springer eBooks(pp. 2843–2872). https://doi.org/10.1007/978-3-319-68255-6_70*

- *Rafa, N., Ahmed, B., Zohora, F. T., Bakya, J., Ahmed, S. F., Ahmed, S. F., Mofijur, M., Chowdhury, A. A., & Almomani, F. (2024). Microplastics as carriers of toxic pollutants: Source, transport, and toxicological effects. Environmental Pollution, 343, 123190. https://doi.org/10.1016/j.envpol.2023.123190*

- *Randall, C. (2023, January 17). Speedland SL:PDX Review. iRunFar. https://www.irunfar.com/speedland-slpdx-review*

- *Ritzen, L., Sprecher, B., Bakker, C., & Balkenende, R. (2023). Bio-based plastics in a circular economy: A review of recovery pathways and implications for product design. Resources, Conservation and Recycling, 199, 107268. https://doi.org/10.1016/j.resconrec.2023.107268*

- *Runner’s World How sustainable are your running shoes? (2023, March 29). Runner’s World. https://www.runnersworld.com/uk/gear/shoes/a43387630/sustainable-running-shoes/*

- *Shoe components. (n.d.). https://www.runningwarehouse.com/learningcenter/gear_guides/footwear/shoe-components.html*

- *Speedland. (n.d.). Speedland | The world’s first Hyper-Performance trail shoe. https://www.runspeedland.com/*

- *Stanton, T. H., Kay, P., Johnson, M. F., Chan, F. K. S., Gomes, R. L., Hughes, J. D., Meredith, W., Orr, H. G., Snape, C. E., Taylor, M. S., Weeks, J. C., Wood, H., & Xu, Y. (2020). It’s the product not the polymer: Rethinking plastic pollution. WIREs Water, 8(1). https://doi.org/10.1002/wat2.1490*

- *Store, S. R. (n.d.). TRAIL RUNNING SHOES – What you need to know! Strides Running Store. https://www.stridesrunning.com/blogs/helpful-tips/trail-running-shoes-what-you-need-to-know*

- *Sánchez, C. (2023a, November 9). Running shoe upper: how to choose the best one for your needs. RunRepeat - Athletic Shoe Reviews.*

https://runrepeat.com/guides/running-shoe-upper-how-to-choose-the-best-one-for-your-needs

- *Sánchez, C. -b (2023, July 24). In-depth insights into running shoe outsoles (road & trail). RunRepeat - Athletic Shoe Reviews. https://runrepeat.com/guides/insights-into-road-and-trail-running-shoe-outsoles*

- *Team, T. (2023, September 12). How do you know if your packaging is compostable? TIPA. https://tipa-corp.com/blog/how-do-you-know-if-your-packaging-is-compostable/*

- *The biological cycle of the butterfly diagram. (2022, May 23). https://www.ellenmacarthurfoundation.org/articles/the-biological-cycle-of-the-butterfly-diagram*

- *Tonti, L. (2023, January 5). Running in circles: the race to create a recyclable sneaker. The Guardian. https://www.theguardian.com/fashion/2023/jan/05/running-in-circles-the-race-to-create-a-recyclable-sneaker*

- *University of New England. (2022, May 20). What is your footprint leaving behind? University of New England (UNE). https://www.une.edu.au/connect/news/2021/11/what-is-your-footprint-leaving-behin*

- *Van Den Oever, M., Molenveld, K., Van Der Zee, M., & Bos, H. (2017). Bio-based and biodegradable plastics : facts and figures : focus on food packaging in the Netherlands. https://doi.org/10.18174/408350*

- *Van Grinsven, S., & Schubert, C. J. (2023). Soil-biodegradable plastic films do not decompose in a lake sediment over 9 months of incubation. Biogeosciences, 20(19), 4213–4220. https://doi.org/10.5194/bg-20-4213-2023*

- *Yee, M. S., Hii, L., Looi, C., Lim, W., Wong, S. F., Kok, Y., Tan, B., Wong, C. S., & Leong, C. (2021). Impact of microplastics and nanoplastics on human health. Nanomaterials, 11(2), 496. https://doi.org/10.3390/nano11020496*

Figures

- *Background cover:*
  Close side shot Microplastics lay on Stockfoto 2152392547 | Shutterstock. (n.d.). Shutterstock. https://www.shutterstock.com/nl/image-photo/close-side-shot-microplastics-lay-on-2152392547

- *Fig. 1*
  EUBIO_Admin. (n.d.). Bioplastics. European Bioplastics e.V. https://www.european-bioplastics.org/bioplastics/

- *Fig.2*
  Managed Organic Recyling, Inc (MOR) profile. (n.d.). Environmental Expert, S.L. https://www.environmental-expert.com/companies/managed-organic-recyling-inc-42555

- *Fig.3 -4*
  Diamond, D. (2024, January 21). Balena's new partnership VivoBiome featured in The Guardian. Balena Science. https://balena.science/blogs/spotlights/balenas-new-partnership-vivobiome-featured-in-the-guardian

- *Fig. 5*
  Eco-Friendly Shoes Made from Plant-Based Materials | BLUEVIEW. (n.d.). https://blueviewfootwear.com/pages/eco-friendly-materials

- *Fig. 6*
  For ever®. (n.d.). For Ever® - Bio. https://www.forever.pt/en/advanced_sustainable_solutions/thermoplastic_2/thermoplastic_bio

- *Fig. 7*
  C Crystal Lemon 50 counts compostable trash bags, 6 gallon heavy duty trash bags and kitchen garbage bags. (n.d.). https://www.gosupps.com/c-crystal-lemon-50-counts-compostable-trash-bags-6-gallon-heavy-duty-trash-bags-and-kitchen-garbage-bags.html

- *Fig. 8*
  Buchholz, O. (n.d.). Global bioplastics production defies challenges by showing significant increase. European Bioplastics e.V. https://www.european-bioplastics.org/global-bioplastics-production-defies-challenges-by-showing-significant-increase/

- *Fig. 9*
  The butterfly diagram: visualising the circular economy. (n.d.). https://www.ellenmacarthurfoundation.org/circular-economy-diagram?gad_source=1&gclid=EAIaIQobChMIjpD-xua-hAMV-5SDBx0qCAtaEAAYASAAEgIZ8_D_BwE

- *Discover & Analysis cover*
  How long do trail running shoes last? (n.d.). inov-8.com. https://www.inov-8.com/eu/how-long-do-trail-running-shoes-last

- *Fig. 11*
  Petruny, M. (2022, August 9). RW+ exclusive: What can you learn from your running shoes' outsoles? Runner's World. https://www.runnersworld.com/gear/a40836622/rw-plus-exclusive-running-shoe-outsole-test/

- *Fig. 12*
  Forster, N., Wilson, S. C., & Tighe, M. (2023). Trail running events contribute microplastic pollution to conservation and wilderness areas. Journal of Environmental Management, 331, 117304. https://doi.org/10.1016/j.jenvman.2023.117304

- *Fig. 13*
  Race to the Stones 2024 | Sat 13 Jul | Book @ Findarace. (2023, July 12). findarace.com (UK). https://findarace.com/events/race-to-the-stones

- *Fig. 14*
  CyclonTM : running gear designed to be recycled. (n.d.). On Netherlands. https://www.on.com/en-nl/collection/cyclon

- *Fig. 15-16-17*
  adidas unlocks a circular future for Sports with Futurecraft.loop: a performance running shoe made to be remade. (2019, April 17). Adidas News Site | Press Resources for All Brands, Sports and Innovations. https://news.adidas.com/running/adidas-unlocks-a-circular-future-for-sports-with-futurecraft.loop--a-performance-running-shoe-made-t/s/c2c22316-0c3e-4e7b-8c32-408ad3178865

- *Fig. 18*
  How to choose running shoes. (n.d.). REI. https://www.rei.com/learn/expert-advice/running-shoes.

- *Fig. 20*
  Salomon. (n.d.). Salomon Wildcross 2 Trail Running Shoes Red | Runnerinn. https://www.tradeinn.com/runnerinn/en/salomon-wildcross-2-trail-running-shoes/138135294/p

- *Fig. 21*
  Asics Gel-Trabuco 9 1012A904 Black/Baltic Jewel 002 | ecipele.hr. (n.d.). ecipele.hr. https://ecipele.hr/p/obuca-asics-gel-trabuco-9-1012a904-black-baltic-jewel-002

- *Fig. 22*
  Lycan II. (n.d.). https://www.runningxpert.com/nl/la-sportiva-women-s-lycan-ii-46i-639638.html

- *Fig. 23-24-25*
  Dombroski, C. (2022, December 20). When to replace worn out footwear | SoleScience. SoleScience - Orthotics, Gait Analysis & Individualized Pedorthic Care. https://www.solescience.ca/how-worn-is-worn-out/

- *Fig.26-27*
  Speedland. (n.d.). Speedland | The world's first Hyper-Performance trail shoe. https://www.runspeedland.com/

- *Fig.28-29*
  ISPO Award - Infinite ONE. (n.d.). ISPO.com. https://www.ispo.com/en/ispo-award/2021/infinite-one

- *Fig., 30*
  Arcuri, A. (2023, December 6). 10 best trail running shoes. GearLab. https://www.outdoorgearlab.com/topics/shoes-and-boots/best-trail-running-shoes

- *Material Exploration cover*
  EU-Startups. (2020, May 5). Woodly | EU-Startups. https://www.eu-startups.com/directory/woodly/

- *Fig. 31-32*
  PTT MCC is a strategic joint venture company between PTT Global Chemical Public Company Limited (GC) and Mitsubishi Chemical Corporation (MCC). (n.d.). https://www.pttmcc.com/what-is-biopbs

- *Fig. 33*
  Ghosh, K., & Jones, B. H. (2021). Roadmap to Biodegradable Plastics—Current state and research needs. ACS Sustainable Chemistry & Engineering, 9(18), 6170–6187. https://doi.org/10.1021/acssuschemeng.1c00801

- *Fig. 34*
  Plastics, S. (2021, October 14). The tussle in Brussels: is PHA a naturally occurring polymer? Or a plastic? Sustainable Plastics. https://www.sustainableplastics.com/news/tussle-brussels-pha-naturally-occurring-polymer-or-plastic

- *Fig. 35*
  Yousuf, R. (2018). NOVEL POLYHYDROXYBUTYRATE (PHB) PRODUCTION USING a WASTE DATE SEED FEEDSTOCK. ResearchGate. https://www.researchgate.net/publication/337593093_NOVEL_POLYHYDROXYBUTYRATE_PHB_PRODUCTION_USING_A_WASTE_DATE_SEED_FEEDSTOCK

- *Fig. 36-37*
  PHA Filaments - Materials - FILAMENTEN. (n.d.). https://colorfabb.com/nl/filaments/materials/pha-filaments

Appendix

Project brief

DESIGN FOR our future

TUDelft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	Balboni 6832	IDE master(s)	IPD ✓ Dfl SPD
Initials	MB	2nd non-IDE master	
Given name	Matteo	Individual programme *(date of approval)*	
Student number	5617111	Medisign	
		HPM	

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Conny Bakker	dept./section	SDE
mentor	Puck Bos	dept./section	SDE
2nd mentor			
client:			
city:		country:	
optional comments	Chair has in-depth knowledge of circular design, mentor is experienced industrial designer who, as PhD, is now becoming an expert on designing with bio-based plastics. This makes the supervisory team complementary.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Conny Bakker

Digitally signed by Conny Bakker
Date: 2023.09.27 08:21:08 +02'00'

Name Conny Bakker | Date 27 Sep 2023 | Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total	54	EC
Of which, taking conditional requirements into account, can be part of the exam programme	30	EC

★	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Robin den Braber — Digitaal ondertekend door Robin den Braber Datum: 2023.09.29 08:19:43 +02'00'

Name: Robin den Braber Date: 29 sept 2023 Signature

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen — Digitally signed by Monique von Morgen Date: 2023.10.03 11:53:40 +02'00'

Name: Monique von Morgen Date: 3 Oct 2023 Signature

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Name student Matteo Balboni **Student number** 5,617,111

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Footprints for the Future: Designing Shoes with Biodegradable Plastics

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Plastics, present in various aspects of our daily lives, have greatly improved our society but now pose significant threats to the environment and human health (1). The proliferation of microplastics, in particular, has become a global pollution concern due to its associated carbon emissions and the persistence of plastics, disrupting ecosystems (1).

Shoes, essential and fashionable items, are often made with environmentally harmful materials and adhesives, with synthetic rubber soles contributing to soil ecosystem degradation through abrasion-generated fragments (2). During activities such as triathlons and trail running, the risk of causing harm to the environment is higher.

One solution is the use of biodegradable and compostable plastics, which could be consumed by microorganisms, mitigating climate change, microplastic pollution, and littering issues. However, their limited market share and the need for further research and commercialization pose challenges (1).

Exploring biodegradable plastics in shoe design involves key stakeholders such as shoe manufacturers, waste management authorities, environmentally-conscious consumers, and environmental organizations. Opportunities include raising consumer awareness, integrating biodegradable plastics into shoe production, technological advancements, and collaborative innovation. Nevertheless, challenges like material availability, cost, cultural norms favouring traditional materials, recycling infrastructure, durability, and regulatory compliance complexities must be addressed.

Analyzing these stakeholders and considering the opportunities and limitations is essential for the development of sustainable footwear. This effort not only benefits current society but also ensures a brighter future for the generations to come.

1) Filiciotto, L., & Rothenberg, G. (2020). Biodegradable plastics: Standards, policies, and impacts. Chemsuschem, 14(1), 56–72. https://doi.org/10.1002/cssc.202002044

2) Lee, T., Kim, L., Kim, D., An, S. H., & An, Y. (2022). Microplastics from shoe sole fragments cause oxidative stress in a plant (Vigna radiata) and impair soil environment. Journal of Hazardous Materials, 429, 128306. https://doi.org/10.1016/j.jhazmat.2022.128306

→ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1 Adidas Futurecraft Biofabric

image / figure 2 Balena, BioCycling in Action

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The project aims to address the growing environmental concern of microplastic pollution caused by conventional shoes. The specific issue to be tackled is the need for sustainable and eco-friendly alternatives in shoe manufacturing to mitigate microplastic pollution. This project will explore the feasibility and implications of incorporating biodegradable plastics into shoe design, focusing on key components, such as soles, lasts, laces, vamps, and toe boxes, (with a particular emphasis on shoe soles), taking into account both functional and environmental aspects.

The research will be structured into three key components: material investigation, environmental assessment, and end-of-life considerations. Material Investigation will involve an in-depth exploration of biodegradable plastic materials suitable for shoe sole applications, including factors like durability, performance, comfort and environmental impact. Environmental assessment will investigate a comprehensive evaluation of the environmental advantages and limitations of biodegradable plastics compared to conventional materials.
Finally, end-of-life considerations will involve examining how integrating biodegradable shoe components can modify the product's life cycle assessment.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Designing shoes with bio-based and naturally biodegradable plastic, to evalute a product that drastically minimizes micro-plastic pollution.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Conducting satisfactory literature research on biobased, compostable plastic and microplastic pollution is crucial for the success of this project. Moreover, it is important to analyse the current shoe line production, identifying the most commonly used materials, and understanding their key properties that make them suitable for their respective purposes. Afterwards, a critical step involves exploring the market for new, sustainable materials, (especially bio-based alternatives), and contacting companies to request material samples and info. Additionally, software such as Granta EduPack will help in comparing different materials and gaining a clearer understanding of the energy and consumption required for different materials.

Meanwhile, in parallel with the research phase, there will be the ideation stage, with thumbnail sketches, lo-fi prototypes and a constant iteration during the first weeks. Regarding the conceptualization, the creative process will be guided by the Double Diamond Model. This phase will be divided into divergent and convergent solutions, allowing for a comprehensive exploration of potential ideas. Throughout the ideation process, including sketches, renders, prototypes and reviews with mentor and chair. Refining and enhancing the final design concept can be achieved by seeking feedback and suggestions and conducting interviews and user tests .

The final stage of the project involves selecting a final design, which will serve as a proof of concept for a 1:1 prototype. This prototype will provide a tangible representation of the work done over the past five months.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting, mid-term evaluation meeting, green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	25 Sep 2023
Mid-term evaluation	27 Nov 2023
Green light meeting	1 Feb 2024
Graduation ceremony	29 Feb 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

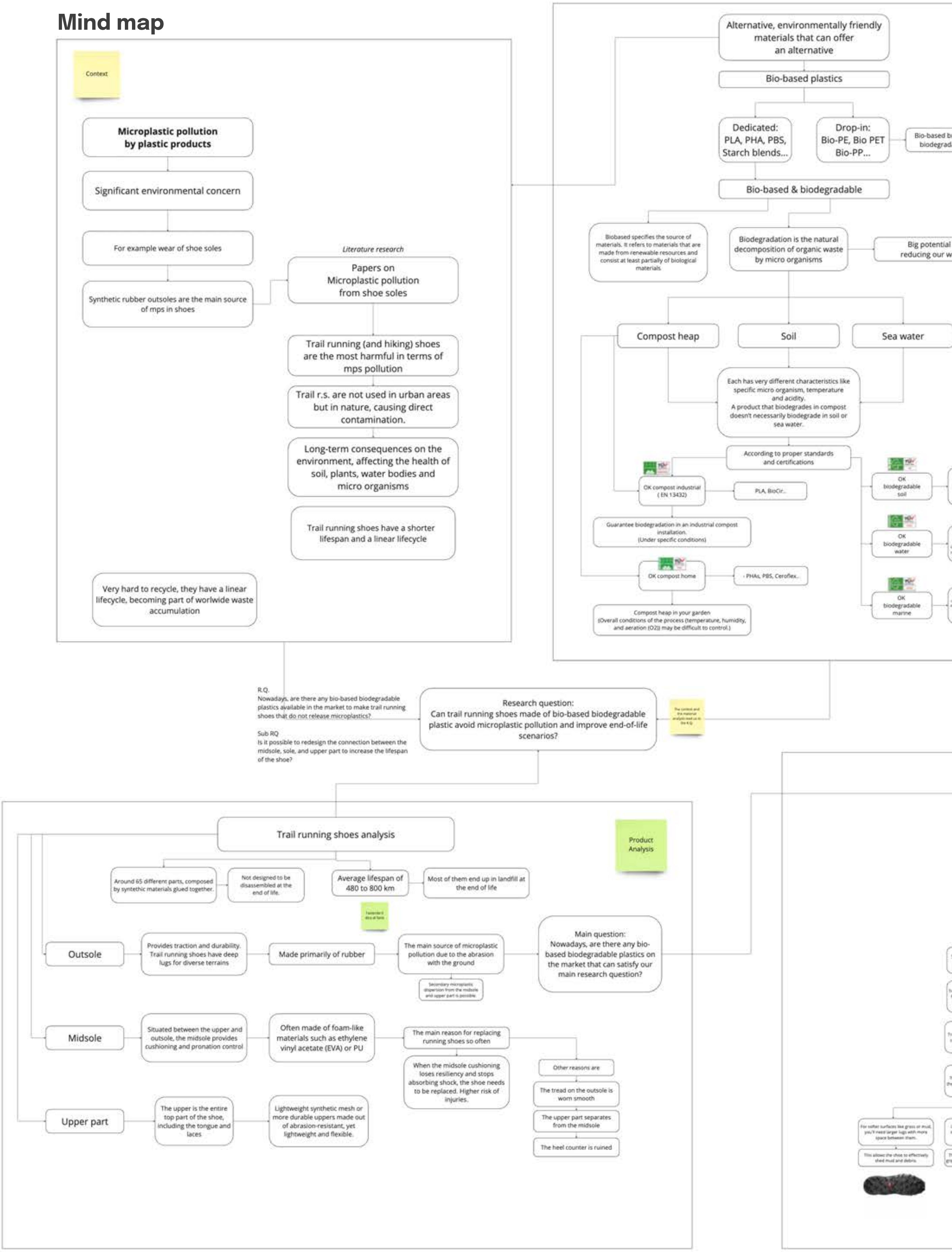
I chose to work on this project because it perfectly aligns with my personal interests. Sustainability is a core concern of mine as a designer, and I am deeply enthusiastic about exploring how bio-based materials can positively influence the entire lifecycle of a product.

Being an industrial designer in 2023 presents several challenges, especially in a world overcrowded with objects and products. However, our society cannot entirely live without these items, making it imperative for designers, engineers, and manufacturers to design sustainable products with a circular economy strategy. These products should have a minimal environmental impact, be designed to last, be easy to repair or update, and be conducive to recycling.

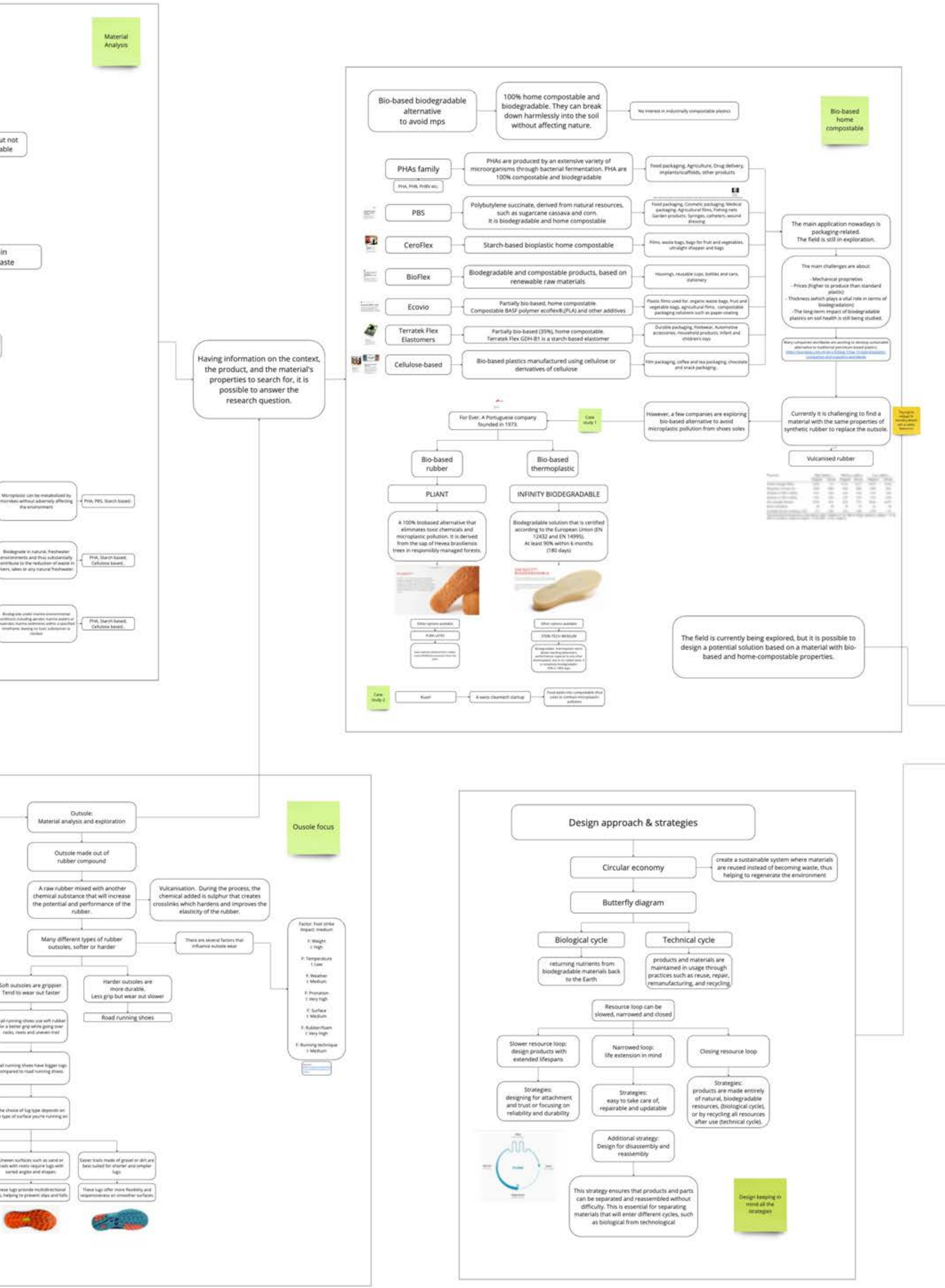
During my second year in the Integrated Product Design program, I did a similar project for the AED course. It was about designing a bicycle helmet (for BBB bicycles) able to replace EPS, a material harmful to the environment, which is commonly used in helmets due to its properties and affordability. This project was both challenging and inspiring, reinforcing my belief that designing the next generation of products with particular attention to the environment is the right path to pursue.

I have multiple expectations for this project. I aim to gain a comprehensive understanding of the latest bio-based materials currently available, exploring their optimal applications and limitations. Moreover, this project presents an opportunity to acquire knowledge on the proper design of shoes, not solely for aesthetic considerations but also to fulfil functional and environmental needs.

Mind map



Context
Microplastic pollution by plastic products
Significant environmental concern
For example wear of shoe soles
Synthetic rubber outsoles are the main source of mps in shoes
Literature research
Papers on Microplastic pollution from shoe soles
Trail running (and hiking) shoes are the most harmful in terms of mps pollution
Trail r.s. are not used in urban areas but in nature, causing direct contamination.
Long-term consequences on the environment, affecting the health of soil, plants, water bodies and micro organisms
Trail running shoes have a shorter lifespan and a linear lifecycle
Very hard to recycle, they have a linear lifecycle, becoming part of worlwide waste accumulation
Alternative, environmentally friendly materials that can offer an alternative
Bio-based plastics
Dedicated: PLA, PHA, PBS, Starch blends...
Drop-in: Bio-PE, Bio PET Bio-PP...
Bio-based & biodegradable
Biobased specifies the source of materials. It refers to materials that are made from renewable resources and consist at least partially of biological materials.
Biodegradation is the natural decomposition of organic waste by micro organisms
Compost heap
Soil
Sea water
Each has very different characteristics like specific micro organism, temperature and acidity. A product that biodegrades in compost doesn't necessarly biodegrade in soil or sea water.
According to proper standards and certifications
OK compost industrial (EN 13432)
PLA, BioCir...
Guarantee biodegradation in an industrial compost installation. (Under specific conditions)
OK compost home
- PHAs, PBS, Ceroflex...
Compost heap in your garden (Overall conditions of the process (temperature, humidity, and aeration (O2)) may be difficult to control.)
OK biodegradable soil
OK biodegradable water
OK biodegradable marine
R.Q.
Nowadays, are there any bio-based biodegradable plastics available in the market to make trail running shoes that do not release microplastics?
Sub RQ
Is it possible to redesign the connection between the midsole, sole, and upper part to increase the lifespan of the shoe?
Research question:
Can trail running shoes made of bio-based biodegradable plastic avoid microplastic pollution and improve end-of-life scenarios?
Trail running shoes analysis
Product Analysis
Around 65 different parts, composed by syntethic materials glued together.
Not designed to be disassembled at the end of life.
Average lifespan of 480 to 800 km
Most of them end up in landfill at the end of life
Outsole
Provides traction and durability. Trail running shoes have deep lugs for diverse terrains
Made primarily of rubber
The main source of microplastic pollution due to the abrasion with the ground
Main question:
Nowadays, are there any bio-based biodegradable plastics on the market that can satisfy our main research question?
Midsole
Situated between the upper and outsole, the midsole provides cushioning and pronation control
Often made of foam-like materials such as ethylene vinyl acetate (EVA) or PU
The main reason for replacing running shoes so often
When the midsole cushioning loses resiliency and stops absorbing shock, the shoe needs to be replaced. Higher risk of injuries.
Other reasons are
The tread on the outsole is worn smooth
The upper part separates from the midsole
The heel counter is ruined
Upper part
The upper is the entire top part of the shoe, including the tongue and laces
Lightweight synthetic mesh or more durable uppers made out of abrasion-resistant, yet lightweight and flexible.


Material Analysis
Having information on the context, the product, and the material's properties to search for, it is possible to answer the research question.
Bio-based biodegradable alternative to avoid mps
100% home compostable and biodegradable. They can break down harmlessly into the soil without affecting nature.
Bio-based home compostable
PHAs family
PHAs are produced by an extensive variety of microorganisms through bacterial fermentation. PHA are 100% compostable and biodegradable
PBS
Polybutylene succinate, derived from natural resources, such as sugarcane cassava and corn. It is biodegradable and home compostable
CeroFlex
Starch-based bioplastic home compostable
BioFlex
Biodegradable and compostable products, based on renewable raw materials
Ecovio
Partially bio-based, home compostable. Compostable BASF polymer ecoflex®,(PLA) and other additives
Terratek Flex Elastomers
Partially bio-based (35%), home compostable. Terratek Flex GDH-B1 is a starch-based elastomer
Cellulose-based
Bio-based plastics manufactured using cellulose or derivatives of cellulose
The main application nowadays is packaging-related. The field is still in exploration.
Currently it is challenging to find a material with the same properties of synthetic rubber to replace the outsole.
Vulcanised rubber
However, a few companies are exploring bio-based alternative to avoid microplastic pollution from shoes soles
For Ever. A Portuguese company founded in 1973.
Case study 1
Bio-based rubber
Bio-based thermoplastic
PLIANT
INFINITY BIODEGRADABLE
A 100% biobased alternative that eliminates toxic chemicals and microplastic pollution. It is derived from the sap of Hevea brasiliensis trees in responsibly managed forests.
Biodegradable solution that is certified according to the European Union (EN 13432 and EN 14995). At least 90% within 6 months (180 days)
The field is currently being explored, but it is possible to design a potential solution based on a material with bio-based and home-compostable properties.
Case study 2
Outsole: Material analysis and exploration
Ousole focus
Outsole made out of rubber compound
A raw rubber mixed with another chemical substance that will increase the potential and performance of the rubber.
Vulcanisation. During the process, the chemical added is sulphur that creates crosslinks which hardens and improves the elasticity of the rubber.
Many different types of rubber outsoles, softer or harder
There are several factors that influence outsole wear
Harder outsoles are more durable. Less grip but wear out slower
Road running shoes
Design approach & strategies
Circular economy
create a sustainable system where materials are reused instead of becoming waste, thus helping to regenerate the environment
Butterfly diagram
Biological cycle
Technical cycle
returning nutrients from biodegradable materials back to the Earth
products and materials are maintained in usage through practices such as reuse, repair, remanufacturing, and recycling
Resource loop can be slowed, narrowed and closed
Slower resource loop: design products with extended lifespans
Narrowed loop: life extension in mind
Closing resource loop
Strategies: designing for attachment and trust or focusing on reliability and durability
Strategies: easy to take care of, repairable and updatable
Strategies: products are made entirely of natural, biodegradable resources, (biological cycle), or by recycling all resources after use (technical cycle).
Additional strategy: Design for disassembly and reassembly
This strategy ensures that products and parts can be separated and reassembled without difficulty. This is essential for separating materials that will enter different cycles, such as biological from technological
Design keeping in mind all the strategies


NIKE
ISPA LINK
NIKE
CONSIDERED
NIKE
ZVEZDOCHKA
VIBRAM
COMPONENT


DOUBLE THREAD STITCHING
OPENING TO INSERT MIDSOLE & OUTSOLE
THE MIDSOLE HAS NOT YET BEEN INSERTED. MORE SPACE IS REQUIRED.
ADD A TONGUE AS PROTECTION BETWEEN THE ZIPPER AND THE ANKLE
DOUBLE LAYER HEEL COUNTER
CONSIDER THE THICKNESS OF THE FABRIC
THE PATTERN NEEDS FEWER ELEMENTS
THE SHOE NEEDS TO BE WIDER

Technical Datasheet

Technical datasheet
allPHA

colorFabb

Date of issue: September 18th, 2023
Version: v1.0

Description

Our allPHA 3D printing filament (pronounced as Alpha) is the ultimate bioplastic. **P**oly**H**ydroxy **A**lkanoates (PHA) is created by a natural occurring process called fermentation. By feeding bacteria natural sugars and oils, the bacteria create "fat" cells (the PHA). The best thing about PHA? Micro-organisms can eat it again at the end of the product's life.

allPHA is 100% biobased and 100% biodegradable in any biotope, without leaving microplastics.

allPHA is a great material for any project which requires a more sustainable approach. With various end-of-life options, and an inherent fade-into-nature property, allPHA is a truly circular material.

Typical Properties

Mechanical Properties – 3D Printed

	Method	*Value*	*Unit*
Youngs Modulus	Tensile, ISO 527-1A	2500	MPa
Tensile Strength	Tensile, ISO 527-1A	26	MPa
Elongation at break	Tensile, ISO 527-1A	4.5	%
Flexural Modulus	Flexural, ISO 178	1820	MPa
Flexural Strength	Flexural, ISO 178	41	MPa
Impact Strength	Charpy Notch, ISO 179	3.4	kJ/m^2
Hardness	Shore D, ISO 7619	62	Shore D

Mechanical Properties – Injection Molded*

	Method	*Value*	*Unit*
Youngs Modulus	Tensile, ISO 527-1A	1950	MPa
Tensile Strength	Tensile, ISO 527-1A	25	MPa
Elongation at break	Tensile, ISO 527-1A	10.4	%
Flexural Modulus	Flexural, ISO 178	1760	MPa
Flexural Strength	Flexural, ISO 178	41	MPa
Charpy Impact Strength	Charpy Notch, ISO 179	5.9	kJ/m^2
Density	ISO 1183	N/A	g/cm^3

Thermal Properties*

	Method	*Value*	*Unit*
Glass Transition Temp.	DSC, ISO 11357	N/A	˚C
Melting Temp.	DSC, ISO 11357	N/A	˚C
Decomposition Temp.	TGA, ISO 11358	N/A	˚C
Heat Deflection Temp.	HDT-B, ISO 75	130	˚C
Melt Flow Index	MFI, (210˚C/2.16 kg), ISO 1133-A	N/A	g/10min
Melt Flow Index	MFI, (190˚C/1,16 kg), ISO 1133-A	N/A	g/10 min

*These results are obtained from the information provided by the supplier of the raw material

colorFabb B.V.
Bremweg 7
5951 DK Belfeld
The Netherlands

T +31 (0)77 – 4664015
F +31 (0)77 – 3971414
E sales@colorfabb.com
I colorfabb.com

KvK nr: 53498607
VAT nr: NL850902770B01
IBAN: NL54RABO0151849188
BIC: RABONL2U

Technical datasheet
allPHA

colorFabb

Date of issue: September 18th, 2023
Version: v1.0

Filament Specifications

	Unit		
Diameter	mm	1.75	2.85
Max. roundness deviation	mm	± 0.05	± 0.1
Net. Filament weight	g	750	750

Guideline for print settings

	Unit	
Nozzle Temp.	°C	190-200
Bed Temp.	°C	0 / RT / not heated
Bed / surface modification	-	3DLac / Diluted wood glue
Active cooling fan	%	100**
Print Speed	mm/s	40-80
Layer Height	mm	0.1 / 0.27***

**On the second or third layer
*** For 0.4 mm nozzle

Notes

The reported properties are an average of a batch of 3D specimens.
Contrary to most 3D printing materials, allPHA is best printed on a cold plate, so no active heating is required. A heating plate will induce crystallization, which leads to warping of the bottom layers.
The specimens have been printed in XY plane, using 0.2 mm layer height, 100% infill, 0.4 mm nozzle, 200°C nozzle temperature and 0°C bed temperature.

Removal of 3D print

Bigger parts with large, flat bottom surface areas can adhere quite strong to the surface, glass / PEI, or flexplate. In this case, it is advised to heat up the plate to 90°C and wait roughly 15 minutes for the bottom layer to heat through. The heat induces crystallization, which makes it easier for the 3D printed part to release from the plate. With the surface still hot, you need to carefully release the model with a sharp and thin scraper, and make your way underneath the model all around.

Smaller parts with less bottom surface will release easier, especially if the brim is not used. You can still use the same technique as described above if the 3D printed part adheres too much, or if it is very delicate.

colorFabb B.V.
Bremweg 7
5951 DK Belfeld
The Netherlands

T +31 (0)77 – 4664015
F +31 (0)77 – 3971414
E sales@colorfabb.com
I colorfabb.com

KvK nr: 53498607
VAT nr: NL850902770B01
IBAN:
NL54RABO0151849188
BIC: RABONL2U

SONGHAN
Plastic Technology Co., Ltd.

www.lookpolymers.com email : sales@lookpolymers.com

Green Dot TerratekÂ® Flex GDH-B1 Compostable Bioplastic Elastomer

Category : Polymer , Renewable/Recycled Polymer , Thermoplastic , Elastomer, TPE

Material Notes:

GDH-B1 is an elastomeric bioplastic with a diverse range of potential applications. It is a starch-based elastomer that is strong, durable and pliable with an exquisite soft touch. The bioplastic is verified to meet U.S. (ASTM D6400) and E.U. (EN 13432) standards for compostability. This material is suitable for injection molding, profile extrusion, sheet extrusion, blow molding, and blown film.Information provided by Green Dot Holdings.

Order this product through the following link:
http://www.lookpolymers.com/polymer_Green-Dot-Terratek-Flex-GDH-B1-Compostable-Bioplastic-Elastomer.php

Physical Properties	Metric	English	Comments
Density	1.23 g/cc	0.0444 lb/inÂ³	ISO 1183-1
Melt Flow	27 g/10 min @Load 2.18 kg, Temperature 190 Â°C	27 g/10 min @Load 4.80 lb, Temperature 374 Â°F	ISO 1133

Mechanical Properties	Metric	English	Comments
Hardness, Shore A	74	74	ISO 868
Tensile Strength, Ultimate	9.40 MPa	1360 psi	ISO 37
Elongation at Break	>= 600 %	>= 600 %	ISO 37
Modulus of Elasticity	0.00440 GPa	0.638 ksi	ISO 37
Tear Strength	57.0 kN/m	325 pli	ISO 34-1
Compression Set	33 % @Temperature 23.0 Â°C, Time 79200 sec	33 % @Temperature 73.4 Â°F, Time 22.0 hour	ISO 815 or ASTM D395
	82 % @Temperature 70.0 Â°C, Time 79200 sec	82 % @Temperature 158 Â°F, Time 22.0 hour	ISO 815 or ASTM D395

Processing Properties	Metric	English	Comments
Rear Barrel Temperature	149 - 165 Â°C	300 - 329 Â°F	
Middle Barrel Temperature	149 - 165 Â°C	300 - 329 Â°F	
Front Barrel Temperature	149 - 165 Â°C	300 - 329 Â°F	

SONGHAN
Plastic Technology Co., Ltd.

www.lookpolymers.com email : sales@lookpolymers.com

Processing Properties	Metric	English	Comments
Nozzle Temperature	149 - 165 Â°C	300 - 329 Â°F	
Melt Temperature	<= 177 Â°C	<= 350 Â°F	
Drying Temperature	32.2 - 37.8 Â°C @Time 7200 - 10800 sec	90.0 - 100 Â°F @Time 2.00 - 3.00 hour	out of sealed box
	37.8 - 48.9 Â°C @Time 14400 - 18000 sec	100 - 120 Â°F @Time 4.00 - 5.00 hour	out of open box
Moisture Content	<= 0.10 %	<= 0.10 %	

Matteo Balboni
5617111

MSc. Integrated Product Design Thesis
Faculty of Industrial Design Engineering
Delft University of Technology