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The role of biocomposites in the transition of plastics towards environmental sustainability and circular economy

Master's Thesis

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Abstract

The negative environmental effects of plastic materials are a growing global concern. The reliance of plastics on fossil resources and the accumulation of plastic waste in nature has evoked a search for sustainable solutions in plastics. Substituting fossil-based raw materials with bio-based feedstocks and transitioning to a circular economy have thus far been presented as the most promising high-level solutions. Although using bio-based raw materials for plastics has been considered environmentally beneficial, it has also been associated with negative effects on sustainability. Biocomposite materials have emerged as an alternative approach to bio-based materials with possibly less negative environmental effects.

This thesis investigates the role of biocomposite materials in the transition of plastics towards environmental sustainability and circular economy. The study is a qualitative and explorative single-case study, investigating the Finnish plastic sector. The research process included 19 interviews in organizations with different roles in the plastic value chain. The study employs an abductive approach utilizing findings from both empirical data and previous research literature. In addition, the study utilizes an open system modelling of the plastic economy.

The study concludes that biocomposites can bring sustainability benefits by replacing fossil-based plastic, but only in a limited space of applications. A major hurdle for biocomposites is that they are currently unlikely to be recycled in the practical recycling infrastructure. As recycling is mostly limited to plastic packaging, applying biocomposite approaches outside packaging applications can be beneficial. The sustainability of biocomposites may also be improved by developing their recycling. Otherwise, if recycling remains in the current focus areas, other approaches than biocomposites may deliver more sustainability benefits if such approaches have more possibilities for recycling.

The conducted thesis study advances the important discussion on the sustainability of materials substituting fossil-based plastic as they are applied to practical contexts. The study provides suggestions for organizations operating in the plastic value chain, as well as advice for policymakers.

Keywords Biocomposites, Bio-based plastics, Circular economy, Sustainability of plastics, Carbon circulation, Plastic recycling

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Tiivistelmä

Muovien negatiiviset ympäristövaikutukset ovat maailmanlaajuisesti kasvava huolenaihe. Koska muovit ovat riippuvaisia fossiilisista resursseista, ja muovijätteen kertyminen luontoon jatkuu, ratkaisuja muovien kestämättömyyteen etsitään jatkuvasti. Fossiilisten raaka-aineiden korvaamista biopohjaisilla raaka-aineilla sekä kiertotalouteen siirtymistä on esitetty lupaavimmiksi ratkaisuiksi. Vaikka biopohjaisten raaka-aineiden käytön muovien valmistamiseksi ajatellaan olevan ympäristölle hyödyllistä, niiden käyttö on myös liitetty negatiivisiin ympäristövaikutuksiin. Biokomposiittimateriaalit ovat nousseet vaihtoehtoiseksi ratkaisuksi, jolla olisi mahdollisesti vähemmän negatiivisia vaikutuksia ympäristöön.

Tämä diplomityö tarkastelee biokomposiittien roolia muovien siirtymässä kohti ympäristöllistä kestävyyttä ja kiertotaloutta. Tutkimus tarkastelee Suomen muovisektoria tapaustutkimuksena. Tutkimuksessa haastateltiin 19 henkilöä organisaatioista, jotka edustavat eri rooleja muovien arvoketjussa. Tutkimus ottaa abduktiivisen lähestymistavan, ja hyödyntää havaintoja niin empiirisestä aineistosta kuin aikaisemmasta tutkimuskirjallisuudesta. Lisäksi tutkimus hyödyntää mallinnusta muovitaloudesta avoimena systeeminä.

Tutkimuksen löydökset osoittavat, että biokomposiitit voivat saada aikaan kestävyyshyötyjä korvaamalla fossiilipohjaista muovia, mutta vain rajatuissa käyttökohteissa. Merkittävä este biokomposiiteille on niiden kierrättämisen vaikeus käytännön kierrätysinfrastruktuurissa. Koska kierrätysjärjestelmä pitkälti rajautuu muovipakkauksiin, biokomposiittien soveltaminen muualla kuin pakkauksissa voi olla hyödyllistä. Biokomposiittien kestävyyttä voidaan kuitenkin parantaa kehittämällä niiden kierrätystä. Jos kierrätysjärjestelmä jatkossakin keskittyy vain nykyisin kierrätettäviin materiaaleihin, muut lähestymistavat biopohjaisuuden lisäämiseen kuin biokomposiitit voivat olla hyödyllisempiä kestävyyden kannalta, mikäli sellaisilla ratkaisuilla on enemmän kierrätysmahdollisuuksia.

Diplomityö edistää tärkeää keskustelua fossiilipohjaista muovia korvaavien materiaalien kestävyydestä käytännössä. Tutkimustulokset hyödyttävät myös arvoketjun organisaatioita sekä politiikkatoimien tekijöitä.

Avainsanat Biokomposiitit, Biopohjaiset muovit, Kiertotalous, Muovien kestävyys, Hiilen kierto, Muovin kierrätys

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Otaniemi, 20 December 2023

Teemu Mikola

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1 Introduction

This chapter introduces the background for the thesis and motivates why the main research topic is relevant. Moreover, the objectives of the research are elaborated, and the research questions of the study are formulated. Furthermore, the structure of the thesis is outlined.

1.1 Background and motivation

The negative environmental effects of plastics have increasingly received public attention during the past years. Although plastic materials deliver many benefits due to their attractive properties, such as durability, light weight, and low cost (Andrady & Neal, 2009), plastics are associated with a host of negative environmental impacts related to their production, usage, and final disposal (Ellen MacArthur Foundation, 2017; Geyer et al., 2017). The reliance of plastic production on fossil resources is an issue in a world that is struggling to deal with climate change (International Energy Agency, 2018; Palm & Svensson Myrin, 2018). In addition, plastic waste that has accumulated around the globe poses a threat to natural ecosystems (Geyer et al., 2017). Accordingly, societies have started to look for solutions to address the unsustainable nature of the current plastic economy by considering the possibilities of a circular plastic economy, which could potentially decouple the plastic economy from its negative environmental effects (European Commission, 2018; Plastics Europe, 2022b). Simultaneously, many industry actors are aiming for replacing fossil-based raw material resources for plastics with bio-based raw materials, to disconnect the plastic economy from the use of fossil resources (Di Bartolo et al., 2021). Furthermore, bio-based plastics provide opportunities for the plastic industry to potentially capture atmospheric carbon, and thus creating long-term storages of carbon if this mechanism is smartly utilized (de Oliveira et al., 2021; Stegmann et al., 2022; Suh & Bardow, 2022).

However, bio-based plastics have also been connected to negative consequences related to sustainability. The plant-based feedstocks used for contemporary bio-based plastics can also be used for food production, and thus using such plants as feedstock could cannibalize food production (Rosenboom et al., 2022). Moreover, a shift from current fossil feedstocks to bio-based feedstocks would require a massive increase in land and fresh water use for the purposes of growing plastic raw material (Di Bartolo et al., 2021; Palm & Svensson Myrin, 2018). In addition, higher prices make it difficult for bio-based alternatives to compete with fossil-based commodity plastics (Acquavia et al., 2021).

As a potential alternative, an innovative material class called biocomposites has emerged. Biocomposite materials offer a paradigm shift in how bio-based content may be introduced into plastics: instead of producing the plastic itself from bio-based raw materials, a material could be produced by blending bio-based substances directly to plastic, thereby decreasing the plastic content in the material (Kamau-Devers & Miller, 2020; Shanmugam et al., 2021; Soroudi & Jakubowicz, 2013). The biocomposite approach could, ideally, address many of the issues related to bio-based plastics, because such materials can utilize side-streams from other production processes, which are considered abundant, available, and generally cheap (Mohanty et al., 2018; Shanmugam et al., 2021). Thus, bio-based content could be added without increasing land use and cannibalizing food production, and perhaps adding cheap bio-based material content could also help with the competitiveness issues of bio-based plastics. Biocomposite materials have been vastly investigated in material technology research (Mahmud et al., 2021; Mohanty et al., 2018; Shanmugam et al., 2021), and the first commercial applications have entered the market (e.g., Stora Enso, 2019; UPM, 2020).

However, although biocomposite materials are generally considered and marketed as sustainable alternatives to fossil-based plastic, it is less understood how their theoretical capabilities translate to practical benefits. As many industry players, as well as material technology researchers, are actively investigating biocomposite materials, it is imperative to understand how the industry and value chain see their role in the broader plastic economy which is aiming to accomplish a sustainability transition. Against this background, this thesis aims to create more understanding of the holistic effects that biocomposites have on the practical plastic value chain. Thus, the study advances the important discussion of understanding possible solutions to the current unsustainability of the plastic economy.

1.2 Research objectives and questions

The purpose of this study is to examine the role of biocomposite materials within the transition of the plastic economy into environmental sustainability and circular economy. The study purposefully departs from purely material technology-oriented research, and rather examines biocomposite materials from a practical and holistic standpoint. Although biocomposite materials address especially the aims of the plastic industry to decouple plastics from fossil-based resources, this study acknowledges that it is less understood what impacts biocomposites could have on the overall sustainability transition of plastics, a critical element of which is the simultaneous transition towards a circular economy. This study therefore aims to evaluate biocomposite materials from a holistic perspective, thus advancing the discussion regarding biocomposite materials as a potential approach in increasing the sustainability of plastic materials.

The objectives of the study can be summarized in three main points. Firstly, the study aims to exploratively investigate the implications that biocomposites introduce to the plastic value chain. This involves a comprehensive analysis of how the integration of biocomposites influences various stages of the value chain. In this investigation, the study adopts a lifecycle perspective, where it critically examines the entire value chain of plastic materials, from raw material extraction to the production, usage, and final disposal. This holistic approach aims to enable a thorough understanding of the environmental impact and sustainability considerations associated with introducing biocomposite materials. Secondly, the study aims to gain insight into the borderline conditions under which biocomposites can serve as means to increase the bio-based content of plastic materials. In this effort, the study aims to delve into the technical, economic, and environmental factors that may influence the successful integration of bio-based content into plastic value chains with the biocomposite approach. Thirdly, the study aims to identify the implications of biocomposites for the simultaneous efforts of the plastic economy to transition towards circular practices. Within this investigation, the study assesses how biocomposites contribute to circularity, recycling processes, and overall sustainability within the plastic value chain.

To address these objectives of the study, the following main research question is then formulated to orient the research:

> *RQ: How can biocomposite materials contribute to the environmental sustainability and circular economy of plastics across the plastic value chain?*

To answer the main research question in a thorough way, the study sees it necessary to also formulate three sub-questions that describe more accurately and granularly what the study aims to investigate. The formulated sub-questions reflect that the analysis examines different lifecycle stages of plastic materials in the plastic value chain. Firstly, it is especially important for the study to understand how biocomposite materials may act as an alternative approach to increasing bio-based content in plastics. Although previous research has demonstrated that biocomposites can be an attractive material (Civancik-Uslu et al., 2018; Kamau-Devers & Miller, 2020;

Shanmugam et al., 2021), it is less understood how the practical plastic value chain sees their viability as an alternative bio-based material, and under what conditions. Thus, the first sub-question is formulated as follows:

> *SQ1: How can biocomposites increase bio-based content in plastics?*

Secondly, the study examines the interaction between biocomposite materials and the general development of plastics towards a circular economy. Circular economy in the plastic context is seen as one of the cornerstones in decoupling plastics from their negative environmental effects (European Commission, 2018). The adoption of various circular strategies could allow plastic materials and products to circulate more effectively in the economy, and thus plastic materials could have longer service lives while also reducing the need of virgin plastic inputs into the economy as well as the harmful outputs from plastic disposal (Ellen MacArthur Foundation, 2017). In previous research, it is left unclear what implications biocomposite materials could have specifically for the emerging circular economy in plastics. Thus, this study aims to examine this area by formulating the second sub-question as follows:

> *SQ2: How can biocomposites contribute to the emerging circular economy of plastics and extend the service life of plastic materials?*

Thirdly, the study examines the important stage of the plastic lifecycle, namely the stage of final disposal of plastics. The current disposal approaches of plastics generally create negative consequences to the environment by either creating GHG emissions from plastic incineration, or by creating physical plastic waste to the nature through leakages from landfilling or littering (Acquavia et al., 2021; Geyer et al., 2017). However, academic research has recognized that these fates for plastics are not inevitable, but rather there may exist alternative approaches, where the carbon embedded in plastics could even be stored for the long-term (Igalavithana et al., 2022; Schmidt et al., 2019; Singh et al., 2021). As these approaches have been investigated only to a limited extent, so is the understanding of the approaches together with the introduction of biocomposites yet very limited. Thus, the study aims to understand the implications of biocomposites to the final disposal opportunities of plastics by formulating the following third sub-question:

SQ3. How can biocomposites limit emissions and plastic waste from plastic disposal, and promote carbon capture and storage?

To seek answers to the formulated main research question and the three sub-questions, this thesis conducts a qualitative and explorative research study. The study utilizes both existing literature and empirical findings and seeks answers to the research questions using an abductive approach. The research is designed as an embedded single-case study, which investigates the Finnish plastic sector by semi-structured interviews with organizations involved in the plastic value chain in Finland.

1.3 Structure of the thesis

The thesis is structured as follows. In the second chapter, the thesis delves into the background literature required to understand the context plastics and the main findings from previous research work. The broader context of plastic materials is introduced, and their consumption and production patterns are elaborated. Moreover, the environmental issues related to plastics are highlighted. Secondly, the chapter explores the development of bioplastics, the issues associated with them, and the development of biocomposite materials as part of the general emergence of bio-based plastic materials. Thirdly, the thesis reviews literature on the circular economy, which is noted as a concept that aims to fulfil a sustainable transition in many industries and the broader economy. Finally, the literature review discusses the circular economy in the plastic context, including the recycling methods, waste management, and final disposal approaches for plastics. Moreover, it is discussed how the plastic sector may contribute to the wider environmental sustainability of the economy. A summary of the background literature is offered at the end of the second chapter.

In the third chapter, the thesis elaborates on the methodological choices made in the research study. The chapter explains the research approach employed in the study, highlights the main principles by which the study is designed, and discusses the investigated case context. In addition, the chapter describes a conceptual modelling approach that is utilized in the study. Finally, the chapter explains the data collection and analysis procedure, and evaluates what limitations can be identified in the methodological design of the study.

In the fourth chapter, the findings of the empirical part of the study are presented. From the conducted interviews, nine main findings are identified, which are presented categorized into four sections. The fifth chapter integrates the findings from the empirical part of the study with the review of research literature to answer the research questions laid out previously in 1.2. The chapter also discusses the implications that the research has for different stakeholders associated with the plastic industry, including managerial implications for companies in the value chain, policy implications for regulators and government, and theoretical implications to research literature. Finally, the thesis concludes with the sixth chapter providing a summary of the conducted research.

2 Literature review

This chapter explores the background of the research from the literature perspective. First, the chapter discusses the context of plastics as a wide class of materials, and the problems connected to plastics. In the second part, the chapter explores the development of bioplastics as an approach to mitigate the environmental issues of plastics. Thirdly, the chapter discusses the concept of circular economy as a framework for improving environmental sustainability of economic activities. In the fourth part, the chapter connects the context of plastics with the circular economy concept and investigates how the circular economy of plastics has been developed. Finally, the chapter concludes with a synthesis of the background literature. The main research gap, which this thesis aims to address, is also elaborated more specifically.

2.1 The context of plastic materials

In this subchapter, the context of plastic materials is introduced. Firstly, the general background of plastics as a broad and versatile material class is explored. Secondly, the chapter discusses plastic consumption, including the main drivers of plastic use and the main market sectors where plastics have a significant role. Thirdly, the production of plastics is explained, including the main types of plastics and the central production methods. Finally, the chapter elaborates on the environmental problems related to plastics.

2.1.1 Background of plastics

It is difficult to imagine modern life without recognizing the important role that plastic materials have in our everyday living. As ubiquitous materials, plastics shape our living from common household objects to food packaging, and from healthcare to the built spaces around us and even the clothes we are wearing. The success of plastics has been tremendous but also problematic.

Although humans have been using polymer materials already in the ancient times (Andrady & Neal, 2009), the widespread use of plastics started only after the second World War in the 1950s (Andrady & Neal, 2009; Geyer et al., 2017). Since then, the growth of plastic production has substantially overtaken the growth in production of any other material class (Geyer et al., 2017). From the 2 Mt global production of plastics in 1950 (Geyer et al., 2017), in just 70 years the production of plastics has massively grown to 390 Mt in 2021 (Plastics Europe, 2022a).

In some contexts, plastics are thought of as merely one material, but in fact the word ‘plastics’ encompasses hundreds of different polymer materials (Palm & Svensson Myrin, 2018). Nevertheless, only a handful of plastics may be considered as the main commodity plastics: polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polystyrene (PS) (Andrady & Neal, 2009; Plastics Europe, 2022a). These commodity plastics comprise approximately 80% of the volume of used plastics today (Plastics Europe, 2022a).

In general, plastic materials are durable, light, and strong, and can be easily worked, which make them an attractive choice to a vast multitude of purposes (Andrady & Neal, 2009; Geyer et al., 2017). The unrivalled properties combined with their low cost have made them a workhorse bulk material for the modern economy (Ellen MacArthur Foundation, 2017). However, plastics rely heavily on the use of fossil resources and create pollution and greenhouse gas (GHG) emissions, which have a critical impact on the climate and the natural environment (Palm & Svensson Myrin, 2018). In addition, as plastics are durable and resistant to degradation, it is very difficult for nature to disintegrate and absorb the plastic materials (Geyer et al., 2017). As appropriate and wide-spread means to handle the plastic waste have been lacking, plastic material wastes have been accumulating across terrestrial and aquatic ecosystems all over the planet (Geyer et al., 2017; Palm & Svensson Myrin, 2018).

The issues with plastic pollution require a systemic shift towards a more sustainable plastic economy (Ellen MacArthur Foundation, 2017). On the other hand, the modern economy is so reliant on plastics and the benefits they bring that replacing them with something else may be impossible or at least extremely challenging (Palm & Svensson Myrin, 2018). This poses a wicked problem for today’s economies, demanding rising attention from policymakers, industries, and consumers (Ellen MacArthur Foundation, 2017).

2.1.2 Plastic consumption

Today, plastics are used in many critical applications. Generally, plastics have obtained a central role in improving the standard of living in the modern economy and saving other resources. Packaging plastics decrease food waste and prolong the shelf-life of food (Andrady & Neal, 2009; Ellen Mac-

Arthur Foundation, 2017; Palm & Svensson Myrin, 2018). Plastics also deliver public health benefits, as they have a central role in facilitating a clean water supply and water management system (such as storing clean water and piping sewage water) and enable clean medical equipment (Andrady & Neal, 2009).

Plastics also have a critical role in saving energy due to their light weight. Using plastics in packaging instead of heavier packaging materials contributes to significant fuel and energy consumption savings in transporting goods (Andrady & Neal, 2009; Ellen MacArthur Foundation, 2017; Palm & Svensson Myrin, 2018). In the transportation vehicles themselves, such as land vehicles and aircraft, designing parts from light plastics instead of heavier metals brings significant fuel saving benefits (Andrady & Neal, 2009).

The high strength-to-weight ratio of plastics compared to other materials, along with their durability, allows plastics to reduce general material consumption (Andrady & Neal, 2009; Palm & Svensson Myrin, 2018). In addition to their strength, toughness, and durability, plastics combine low-cost with ductility, corrosion resistance, bio-inertness, high thermal and electrical insulation, and non-toxicity, which make them a resource-efficient choice for many applications where they are often chosen over competing materials, such as paper, metals, wood, or glass (Andrady & Neal, 2009).

Figure 1 below reports the largest market sectors where plastic materials are used globally. According to Plastics Europe (2022a), the largest single sector where plastic is globally used is packaging with a share of 44%. The second largest is the building & construction sector (18%), followed by various product manufacturing sectors including automotive (8%), electrical & electronics (7%), household, leisure, and sports sector (7%). In the future, plastic consumption is expected to keep increasing (Ellen MacArthur Foundation, 2017; Palm & Svensson Myrin, 2018).

Like in the various market sectors that utilize plastics as materials, there is also a significant disparity in the duration for which these materials remain in use. According to Geyer et al. (2017), the shortest lifespan of plastic usage is found in packaging applications, where plastics are employed for less than a year and often follow a disposable, single-use approach. On the opposite end of the spectrum, plastic applications in the construction and building industry can have a lifespan of up to 40 years (Geyer et al., 2017).

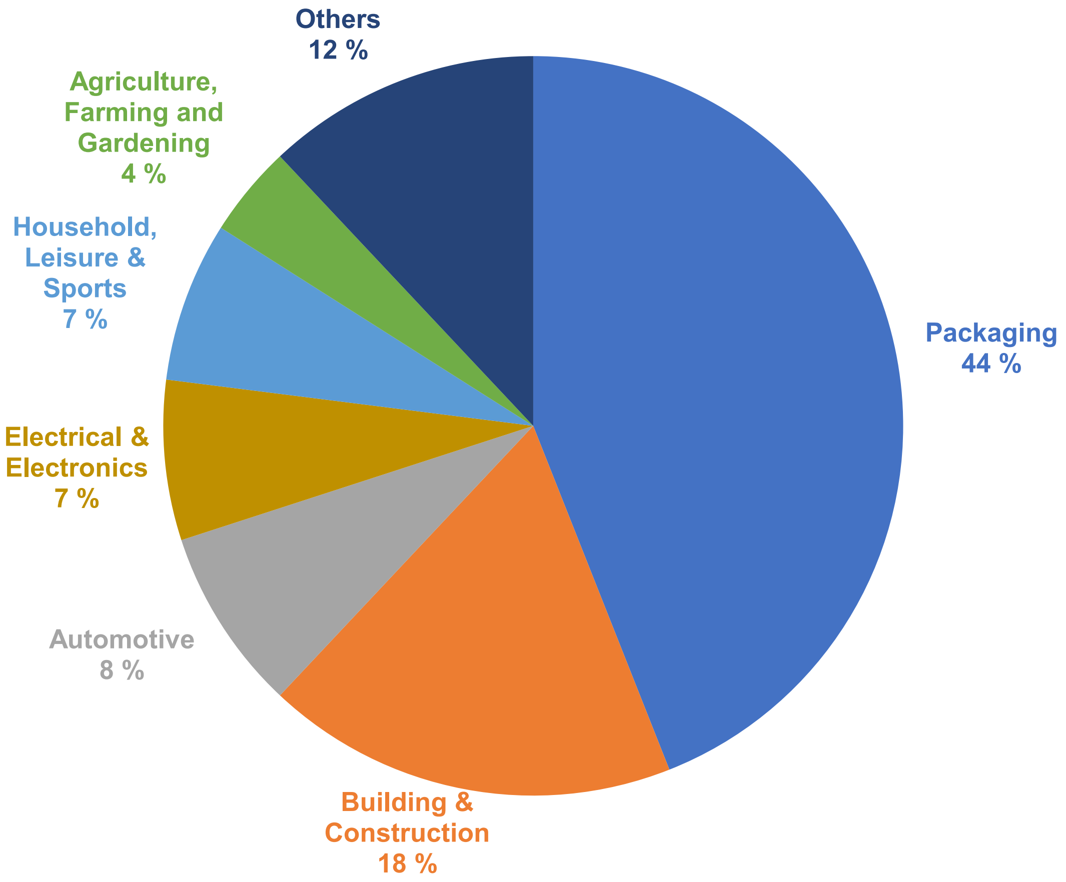


Figure 1: Market sectors of plastic use globally in 2021 (Plastics Europe, 2022a)

2.1.3 Plastic production

After the start of the widespread use of plastics after the second World War, plastics have been the fastest growing bulk material class in terms of production volume (Geyer et al., 2017; International Energy Agency, 2018). According to estimations by Plastics Europe (2022a), the total volume of plastics produced globally surged to 390 million tons in 2021. Table 1 below reports the shares of different plastic types produced. Despite the general diversity of plastic materials, the estimates clearly show that the production and use of plastics are predominantly focused on the few main commodity plastics that comprise most of the production volume.

The main raw material for the current plastics production are fossil resources, namely crude oil, natural gas, and coal (Palm & Svensson Myrin, 2018). It is estimated that the plastic production is responsible for about 4–8% of the total use of fossil resources per year, of which a part is the use of fossil resources as feedstock in the production process and a part the use of fossil energy to power the processes (Andrady & Neal, 2009; Ellen MacArthur Foundation, 2017). For comparison, this is about as much as the annual consumption of global aviation (Ellen MacArthur Foundation, 2017). The plastic production is heavily reliant on virgin fossil resources, and only less than 10% is recycled material (Plastics Europe, 2022a). However, in principle plastics can be derived from any source of hydrogen and carbon (Andrady & Neal, 2009; Palm & Svensson Myrin, 2018). Such a potential source are bio-based sources, which are a growing area but to date still rather marginal in volume (Plastics Europe, 2022a). Bio-based plastics are further introduced later in chapter 0.

Table 1: Production of plastic by type in 2021 (Plastics Europe, 2022a)

	Total global production in 2021	**390 Mt**
Plastic type	**Origin**	**Share (%)**
PP (polypropylene)	Fossil-based	19,3
PE-LD, -LLD (polyethylene, low-, linear low density)	Fossil-based	14,4
PVC (polyvinyl chloride)	Fossil-based	12,9
PE-HD, -MD (polyethylene, high-, medium density)	Fossil-based	12,5
PET (polyethylene terephthalate)	Fossil-based	6,2
PUR (polyurethane)	Fossil-based	5,5
PS (polystyrene)	Fossil-based	5,3
Other fossil-based thermoplastics	Fossil-based	7,1
Fossil-based thermosets (excl. PUR)	Fossil-based	7,1
Recycled plastics	Recycled	8,3
Bio-based plastics	Bio-based	1,5

It is noteworthy to distinguish between two types of plastics that are produced: thermoplastics and thermosets (Palm & Svensson Myrin, 2018). Thermoplastics are plastics that soften when exposed to heat, allowing them to be reshaped and recycled by melting, re-granulation, and reformulation. On the contrary, thermosets are plastics that solidify and cannot be softened or reshaped using heat. A clear majority of the main commodity plastics fall into the category of thermoplastics, except for polyurethane, which are usually thermosets (Andrady & Neal, 2009; Plastics Europe, 2022a).

Plastics are seldom produced or used in their pure polymer form. Typically, additives are introduced to the material, which bring a range of additional properties that aim to increase the functionality of the material for its intended application (Andrady & Neal, 2009; Palm & Svensson Myrin, 2018). These additives encompass a variety of components, such as thermal stabilizers that enable processing at elevated temperatures, plasticizers that enhance pliability and flexibility, fire retardants that prevent ignition and combustion, and UV stabilizers that counteract degradation from sunlight exposure (Andrady & Neal, 2009). Plastics may be blended with fillers to affect the structural integrity of the material, or merely to save polymer consumption by using an inexpensive filler (Palm & Svensson Myrin, 2018). Additionally, colorants, matting agents, opacifiers, and lustre enhancers may be incorporated to elevate the visual appeal of plastic products. Additives are usually the costliest element in the formulation, so they are usually used as minimally as possible (Andrady & Neal, 2009).

From the hydrocarbon feedstocks to the completed plastic product, the plastic production can be categorized to four main stages: raw material refining, polymer production, compounding, and converting (Andrady & Neal, 2009; Palm & Svensson Myrin, 2018; Siltaloppi & Jähi, 2021). Figure 2 below illustrates this production process.

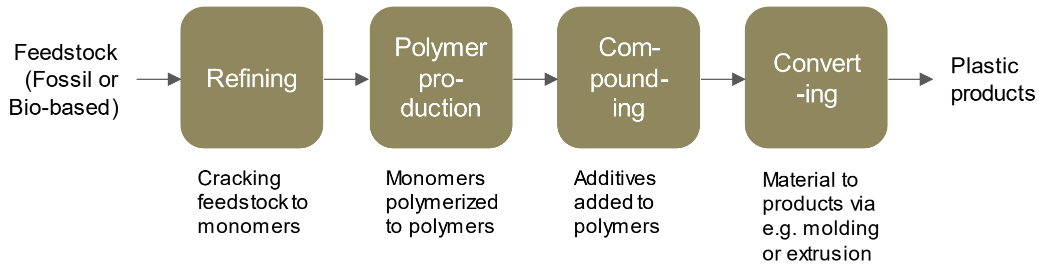


Figure 2: Schematic illustration of the production process of plastics

First, the process starts from fossil or bio-based feedstocks, from which hydrocarbons are extracted by refining and cracking, using various processing technologies, such as steam cracking (International Energy Agency, 2018; Palm & Svensson Myrin, 2018). The production of these hydrocarbons, which are the most basic building blocks, is closely connected to other production processes within the petrochemical industry (International Energy Agency, 2018). As an output from refining and cracking are different monomers, which act again as building blocks for polymers. Second, in polymer production, long molecular chains are polymerized from monomers through either poly-condensation or poly-addition. The finished polymer materials are often delivered as films, pellets, or granulates to the proceeding stages. (Palm & Svensson Myrin, 2018)

Third, the polymers are used as an input in the compounding process, where different additives are typically blended into the material based on desired functionality (Andrady & Neal, 2009; Palm & Svensson Myrin, 2018). Fourth, after compounding the material is ready for the final converting phase, where different converting technologies are used to transform the material into the final plastic product (Palm & Svensson Myrin, 2018; Siltaloppi & Jähi, 2021). Although there are many technologies available, the most common converting technologies are molding and extrusion. In molding, such as injection molding, the material is inserted into a mold as a hot melt to produce a three-dimensional shape. Extrusion, on the contrary, produces shapes of two-dimensional geometries by pressing the material through a nozzle, which creates longitudinal objects from the profile determined by the nozzle. Extrusion is suitable for producing pipes or straws, for example. (Palm & Svensson Myrin, 2018)

To characterize the whole global plastic industry, the global value chain is increasingly complex towards the downstream (EASAC, 2020). According to an industry analysis by KPMG (2023), the upstream parts of global plastic production, i.e., the raw material refining and polymer production are mainly controlled by large and globally operating petrochemical companies, where the production processes demand large capital investments. On the contrary, downstream stages, such as compounding and converting, are highly fragmented industries with smaller organizations (KPMG, 2023). However, large OEMs and brand-owners may possess significant power in the value chain with regards to material choices, the qualities of the materials, as well as prices (KPMG, 2023; Päivölä, 2020).

2.1.4 Environmental problems of plastics

Although plastics are beneficial in many ways as a material choice, the production, use, and end-of-life stages of plastics have major negative impacts on the environment, which render the current plastic economy unsustainable (Ellen MacArthur Foundation, 2017). These environmental challenges of plastics are discussed next. A summarization of the positive and negative environmental effects of plastics is provided below in Table 2.

Table 2: Summary of environmental effects from the use of plastics

Positive effects (+)	**Negative effects (-)**
• In packaging applications, plastics may extend the shelf-life of food and thus limit food waste. • Plastics generally save energy in transportation and vehicles due to their light weight. • As durable and strong materials, they may reduce overall material consumption.	• The use of fossil resources creates GHG emissions. • Plastic waste leaks to the environment and contaminates natural ecosystems. • Microplastics have adverse effects on wildlife and human health. • Chemicals in plastics may be toxic or hazardous.

The first environmental problem of plastics originates from the fact that plastic production heavily relies on fossil resources both as a source of feedstock as well as energy (Andrady & Neal, 2009; Ellen MacArthur Foundation, 2017; Palm & Svensson Myrin, 2018). The use of fossil resources translates to greenhouse gas emissions in different stages of the value chain (International Energy Agency, 2018; Zheng & Suh, 2019), which have a critical impact to global climate change (Rockström et al., 2009; Rosenboom et al., 2022; Stegmann et al., 2022). Especially worrying is that it seems that the petrochemical industry, including plastics production, is becoming the largest driver for global oil consumption (International Energy Agency, 2018). Accounting nowadays for about 4–8% of global oil consumption, it is expected that already in 2050, the plastics sector will account for 20% of global oil consumption (Ellen MacArthur Foundation, 2017). This rising role of plastics in global pollution stresses the importance of focusing on the sector in future emission reduction efforts.

The second environmental problem is connected to the accumulation of the plastic material itself. The same properties that make plastics virtuous for many applications, namely their durability and resistance to degradation, make them problematic from the environmental perspective if not appropriately managed (Andrady & Neal, 2009; Ellen MacArthur Foundation, 2017; Geyer et al., 2017). In natural ecosystems, none of the main commodity plastics can disintegrate or decompose, and so they accumulate in natural environments or landfills (Andrady & Neal, 2009; Geyer et al., 2017; Melchor-Martínez et al., 2022). In a study by Geyer et al. (2017), it was estimated that, in fact, about 4900 Mt of plastics – 79% of all plastics ever produced – had ended up in landfills or the natural environment by 2015. This amount is expected to rise to a worrying 12000 Mt by 2050 (Geyer et al., 2017). For various reasons, including littering, poor waste management systems, and leakage, plastics escape from waste management systems to the nature, and result in a near-permanent contamination of the environment with plastic waste (Ellen MacArthur Foundation, 2017; Geyer et al., 2017; Palm & Svensson Myrin, 2018). For instance, the world's oceans have been estimated to receive 8 Mt of plastic waste every year, and this figure is expected to even quadruple by 2050 (Ellen MacArthur Foundation, 2017).

A crucial element in the plastic waste issue is also the problem of microplastics. Microplastics are small plastic particles, that are released from plastic production or use systems, or as fragments from the partial disintegration of larger plastic wastes (Geyer et al., 2017; Melchor-Martínez et al., 2022; UN Environment Programme, 2023). Microplastics have been found in various ecosystems and environments, such as oceans, and in many species in aquatic and terrestrial environments, posing risks to wildlife (Andrady, 2011; Di Bartolo et al., 2021). They are also a risk to human health (Di Bartolo et al., 2021; UN Environment Programme, 2023), and recently microplastics have even been found in human blood (Leslie et al., 2022). The diffusion of small plastic particles in the environment is a growing concern that has evoked some action so far but requires more actions in the future (Ellen MacArthur Foundation, 2017; UN Environment Programme, 2023).

In addition to microplastics, there are also other health concerns related to plastics. As additives are often used in plastic production, plastic materials often contain complex blends of chemicals (Andrady & Neal, 2009). Some of the substances used as additives may be toxic or hazardous for the health of natural ecosystems as well as humans, such as with different phthalates, flame retardants, bisphenol A, and formaldehyde, to name a few (Acquavia et al., 2021). The potential adverse effects of these substances are concerning and uncertain, which requires further research and efforts to mitigate potential risks (Ellen MacArthur Foundation, 2017).

The environmental problems of plastics also have importance in economic dimensions. In the report by Ellen MacArthur Foundation (2017), it is estimated that, in a global scale, even 95% of the value of the material is lost after the single use of plastics in packaging applications, corresponding to even 80-120 billion US dollars of losses every year (Ellen MacArthur Foundation, 2017). It is further estimated that the negative externality effects of plastics production and use in the consumer goods sector, including the greenhouse gas emissions and plastic waste effects, are valued to even 75 billion US dollars annually to societies (Ellen MacArthur Foundation, 2017). Clearly, the economic losses connected to environmental harm are significant, which however could be prevented by addressing the environmental issues of plastics.

With the environmental problems of plastics combined with the benefits of using plastics, there is a challenging conflict. On one hand, the use of plastics creates environmental benefits by, for instance, improving the resource efficiency of food consumption by extending shelf-lives, or by saving fossil energy in transportation due to lighter weight (Andrady & Neal, 2009). On the other hand, plastics create significant negative effects on the natural environment and the climate if not managed appropriately. Managing this balance is a central challenge to the future of the plastics industry. In the future, plastics must be used in a more efficient way, and use in low value, unnecessary and unsustainable contexts must be addressed (Palm & Svensson Myrin, 2018).

2.2 Bioplastics

This subchapter introduces bioplastics as a specific material class within the wider context of plastics. First, the background and definition of bioplastics are described. In the second section, the benefits and challenges of bioplastics are discussed. Finally, biocomposite materials are introduced as a distinct group of materials within bioplastics.

2.2.1 Background and definition of bioplastics

In recent years, as the awareness of the environmental problems of plastics has increased, the development of bioplastics has received growing attention from the plastic industry as well as scientific research (Acquavia et al., 2021; Palm & Svensson Myrin, 2018). Behind the efforts of developing bioplastics has been the aim to decouple plastic production from fossil feedstocks, as well as to mitigate the environmental effects related to plastic waste (Di Bartolo et al., 2021).

The term 'bioplastics' is often confusing since it encompasses a wide range of materials (Palm & Svensson Myrin, 2018). A generally accepted definition for bioplastics, which is also employed by the European Bioplastics association (2023), identifies bioplastics as materials that fulfil either or both of the following characteristics: 1) the material is *bio-based*, or 2) the material is *biodegradable* (Di Bartolo et al., 2021; European Bioplastics, 2023; Melchor-Martínez et al., 2022). Bio-based refers to polymers that are entirely or partially derived from biomass, which includes organic renewable materials and organic waste (Di Bartolo et al., 2021). In contrast, biodegradable materials have the capacity to undergo decomposition by microorganisms, ultimately transforming into natural elements like carbon dioxide, water, and biomass (Acquavia et al., 2021; Di Bartolo et al., 2021). Biodegradability especially contrasts with the inability of current fossil-based commodity plastics to decompose in nature. Following the illustration from Melchor-Martínez et al. (2022), Figure 3 below illustrates this classification of materials and provides some examples on each class of plastics.

With the two-dimensional classification, three main groups of polymers can be identified as belonging to bioplastics: 1) plastics that are bio-based, but not biodegradable, 2) plastics that are both bio-based and biodegradable, and 3) fossil plastics that are biodegradable (Di Bartolo et al., 2021). The first group constitutes an important class of bioplastics, namely it includes the common commodity plastics that can be made from bio-based feedstocks instead of fossil feedstocks. This group includes bioplastics like bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET) and bio-polypropylene (bio-PP), which are in chemical structure and properties equivalent to the same plastic types from fossil origin (Melchor-Martínez et al., 2022). Since they are chemically identical to the fossil counterparts, they can be easily blended with the same fossil plastic types and used in the exact same processes and applications, which is why they are often called 'drop-in' bioplastics (Shogren et al., 2019). The second group encompasses such plastics as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), bio-based polybutylene succinate (bio-PBS), and various plastics based on starch or cellulose (Di Bartolo et al., 2021). These are typically plastic types of their own, and therefore they possess unique characteristics, production processes, and application possibilities (Shogren et al., 2019). The third group includes examples like polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL) and different oxo-biodegradable plastics, which are based on fossil resources but can degrade in some natural environments (Melchor-Martínez et al., 2022). In terms of volume, the first and second group, i.e., the bio-based plastics are more significant within the realm of bioplastics than the third group which is fossil-based (European Bioplastics, 2023).

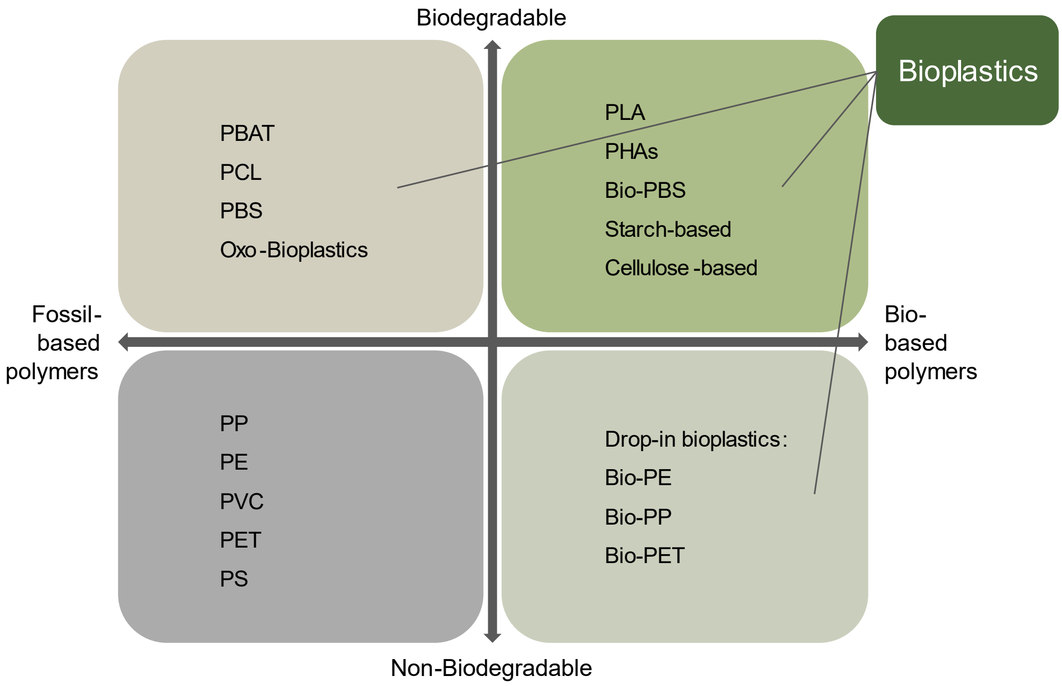


Figure 3: Classification of plastics with example plastic types (Adapted from Melchor-Martínez et al., 2022)

Although bioplastics have received substantial attention during recent years, their significance in the larger plastics context is still marginal. According to European Bioplastics (2023), the global bioplastics production in 2022 was 2.2 Mt, which corresponds to around 1% of the total global plastics production. Nevertheless, the market and production of bioplastics are expected to grow in the coming years (Di Bartolo et al., 2021; European Bioplastics, 2023; Rosenboom et al., 2022). Technically, it is becoming increasingly possible to replace fossil-based plastics with bioplastics in various applications, and in some applications choosing bioplastics can even improve performance of the material (European Bioplastics, 2023).

2.2.2 Benefits and challenges of bioplastics

In comparison to conventional fossil-based plastics, changing the approach to using bioplastics has potential benefits. If bio-based feedstocks are used, it reduces the industry's dependency on fossil resources and can reduce the carbon footprint of the plastic material as the use of fossil resources are replaced by less polluting alternatives (Di Bartolo et al., 2021; European Bioplastics, 2023). In addition, the plant-based resources used for producing bio-based plastics are considered renewable, in contrast to the finite nature of fossil resources (Rosenboom et al., 2022). According to Shogren et al. (2019), bioplastics also consume less energy in their production. Biodegradability, on the other hand, may contribute to mitigating the plastic waste problem. Biodegradable plastics may cause less harm to ecosystems if they would degrade into natural substances in nature, which would be advantageous especially in applications where plastics are likely to leak into the environment (Acquavia et al., 2021; Di Bartolo et al., 2021).

However, bioplastics are also widely seen as problematic. Currently, most of the bioplastics are derived from carbohydrate-rich plants, such as corn, sugar cane, castor oil plant, potato, or wheat, which could be alternatively used as human food or animal feed (Brizga et al., 2020). This is a controversy from an ethical and social sustainability point of view since it is seen as a concern if plastic feedstock production would compete with food production (Rosenboom et al., 2022). These bioplastics based on edible plant resources are often referred to as 'first-generation' bioplastics (Brizga et al., 2020). Bioplastic production should then move towards a 'second-generation', meaning towards feedstocks derived from plants and biomasses that would not have an alternative food use possibility (Brizga et al., 2020; Rosenboom et al., 2022). Example sources could then be some non-food plants, such as wood cellulose, and waste streams from food production such as wheat straw and sugarcane bagasse (Brizga et al., 2020; Rosenboom et al., 2022). Using such feedstocks could be more viable from ethical and sustainability perspectives but would be a more complex source of feedstock (Rosenboom et al., 2022). In addition to the food use concerns, bioplastic production is also on a general level criticized over its implications to land use, as it could significantly reserve arable land away from alternative uses, which is a finite resource (Palm & Svensson Myrin, 2018). Moreover, it is a concern whether bioplastic production causes deforestation in some parts of the world (Rosenboom et al., 2022). In addition to land use, a major concern is also the increased freshwater use, which may considerably increase when cultivating plants appropriate for bioplastic production (Di Bartolo et al., 2021).

Apart from the sustainability concerns related to bio-based feedstocks, biodegradability is also a point of concern. In fact, even though some bioplastics are labelled biodegradable, they may need a very controlled environment to degrade, which may be achieved only in industrial composting (Fredi & Dorigato, 2021). The infrastructure for industrially composting biodegradable plastics is however mostly lacking (Di Bartolo et al., 2021). If such plastics are not appropriately managed and they leak into the environment, they may cause similar environmental problems as conventional plastics if they do not degrade in the receiving environment (Acquavia et al., 2021). Moreover, if biodegradable plastics are not composted in a controlled way and are rather just landfilled, their decomposition releases greenhouse gas emissions (Di Bartolo et al., 2021).

In addition to the concerns related to bio-based feedstocks and biodegradability, there are also other obstacles that hinder the adoption of bioplastics. In general, the mechanical properties of bioplastics are inferior to fossil-based plastics, except in the case of drop-in plastics which can reach the same performance (Fredi & Dorigato, 2021). Moreover, bioplastics have higher production costs than conventional fossil plastics (Acquavia et al., 2021). With the low prices of oil and existing subsidies to fossil resources, it is difficult for bioplastics to be competitive against conventional fossil-based plastics in the industry where profit margins are also narrow (Rosenboom et al., 2022). Furthermore, certain bioplastics, particularly those not classified as drop-in plastics, require distinct manufacturing procedures, and possess unique attributes that limit their potential applications (Shogren et al., 2019). Due to the relatively limited market demand for these materials, there is inadequate incentive for investments aimed at enhancing production and waste management methods that could ultimately reduce the costs of bioplastics (Di Bartolo et al., 2021). However, the drop-in bioplastics and some cost-competitive biodegradable types such as PLA blends and cellulose may encounter fewer obstacles when entering established markets, especially to certain markets where higher margins are possible (Rosenboom et al., 2022).

A summary of the benefits and challenges of bioplastics is presented below in Table 3. To conclude, bioplastics are an emerging field in the plastic industry, encompassing a wide range of materials characterized by their bio-based origin or biodegradability (Di Bartolo et al., 2021). With technological advances they have the potential to replace conventional plastics in many applications and mitigate environmental problems related to the use of plastics (European Bioplastics, 2023). However, they have a limited scale and poor cost-competitiveness, and the environmental benefits they may bring are uncertain and, in some cases, inadequate to create major improvement (Rosenboom et al., 2022).

Table 3: Summary of benefits and challenges of bioplastics

Benefits	**Challenges**
• May reduce the carbon footprint of the plastic material. • Shifts to using renewable resources rather than depending on finite fossil resources. • May consume less energy in production compared to conventional plastics. • Biodegradable plastics may be less harmful if leaked to the environment. • Drop-in plastics reach the same quality as fossil counterparts.	• Bio-based raw materials may compete with food production. • May have significant impacts on land and water use. • Biodegradability generally requires industrial composting. • Poorly managed biodegradation may have negative environmental impacts. • Mechanical properties are generally inferior to conventional plastics. • Bioplastics have high production costs which limit competitiveness.

2.2.3 Biocomposites

Ever since the widespread adoption of plastics, the industry has been actively searching for ways to reduce the costs of plastics. One significant strategy has been to incorporate different fillers into plastic materials, aiming to reduce the overall cost of the material by blending in low-cost substances (Civancik-Uslu et al., 2018). However, introducing fillers may also bring additional functionality to the material by improving its properties or by reinforcing the material (Mohanty et al., 2018; Sanjay et al., 2018). In general, materials consisting of at least two different components that support each other are referred to as *composites* (Civancik-Uslu et al., 2018; Manu et al., 2022). The main components in plastic composites are then the reinforcing material and the polymer matrix, the latter of which is the plastic component that serves to bind the reinforcing material together (Manu et al., 2022). Typical examples of traditional composite materials are glass-fiber reinforced plastics or talc-filled plastics (Mahmud et al., 2021; Shanmugam et al., 2021).

As the field of plastics has begun to note the environmental issues of fossil-based plastics and started gradually to adopt various bioplastics, the field has also seen developments of introducing bio-based fillers to plastics (Manu et al., 2022). These materials, termed as *biocomposites*, have been under major research efforts and increasing interest within different industries that use plastics (Mahmud et al., 2021; Mohanty et al., 2018; Shanmugam et al., 2021). According to a definition by Manu et al. (2022), a biocomposite is a material formed by a natural (usually biological) material as reinforcement and a polymer matrix derived from natural or synthetic sources, which combined result in a material with enhanced properties that surpass those of the individual components. The composition of biocomposites is illustrated in Figure 4 below.

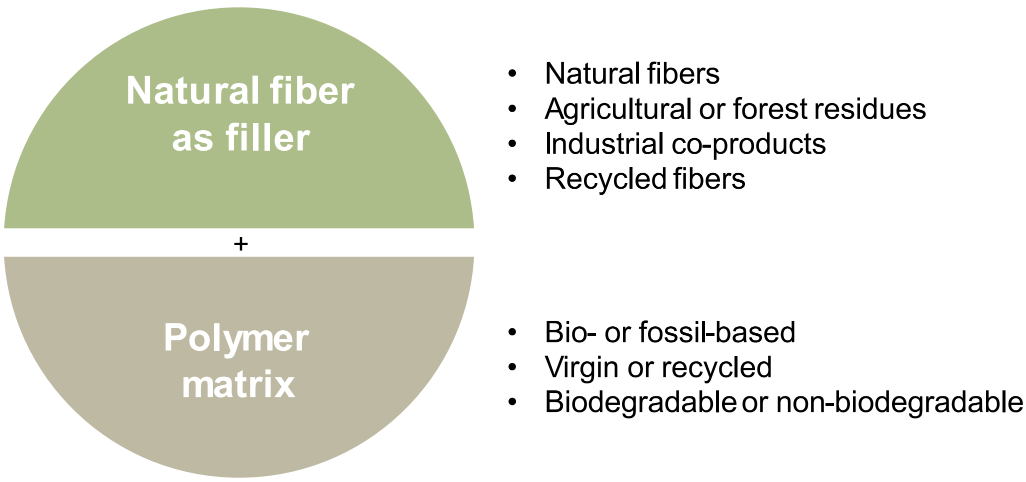


Figure 4: Composition of biocomposite materials
(Adapted from Mohanty et al., 2018)

To design and engineer biocomposites, various combinations of the polymer matrix and reinforcing fillers may be used (Mohanty et al., 2018). As for the filler component, there are a wide range of natural materials that have been explored for use. According to Mohanty et al. (2018), these fillers may be categorized broadly by origin to four main categories: natural fibers, agricultural and forest residues, industrial co-products, and recycled fibers or fillers. The traditional natural fibers encompass materials such as flax, jute, hemp, or wood (Mahmud et al., 2021). Examples of agricultural residues may be wheat, rice, or soy straws, and forest residues may provide woody biomasses that are applicable as fillers (Mohanty et al., 2018). Also, from industrial processing of crops, different co-products can be obtained as a filler such as bagasse, hulls, and husks, and from forest industry side-streams lignin could be used as a filler (Civancik-Uslu et al., 2018; Mohanty et al., 2018). Finally, recycled fillers may be utilized, such as material from cardboard sheets or recycled carbon fibers (Mohanty et al., 2018). The polymer matrix, however, may either consist of a fossil-based or a bio-based polymer, which may be a virgin or recycled polymer (Shanmugam et al., 2021).

The main driver for the increased interest in developing biocomposites relates to their potential for reducing environmental impacts in a cost-efficient way, while possibly also improving material properties (Shanmugam et al., 2021; Soroudi & Jakubowicz, 2013). Biocomposite plastics have generally less impact on the environment than fossil-based counterparts (Civancik-Uslu et al., 2018; Kamau-Devers & Miller, 2020; Shanmugam et al., 2021). This positive impact mainly originates from the capacity of bio-based fillers to substitute fossil-based content in the material (Kamau-Devers & Miller, 2020). Furthermore, introducing bio-based fillers may also provide a reinforcing role in the material, by achieving similar or even better properties than, for example, glass fibers and mineral fillers (Mahmud et al., 2021; Mohanty et al., 2018; Sanjay et al., 2018). However, the material performance is highly determined by the interface between the matrix and the filler, in which the components must be made compatible with different treatment methods to achieve good performance (Mohanty et al., 2018; Sanjay et al., 2018). Nevertheless, the environmental benefits may be substantial, and with a low cost, because many bio-based materials that could be used as fillers are abundant and currently underutilized (Mahmud et al., 2021; Sanjay et al., 2018).

In this study, biocomposite materials are mainly considered as an alternative approach to increasing bio-based content in plastics. As discussed earlier in 0, bioplastics in general face various challenges that limit their adoption and therefore their capacity to create environmental benefits. To this end, biocomposite materials may have potential in solving and overcoming these issues whilst introducing more bio-based content to plastics. The identified potential solutions are summarized in Table 4 below. Firstly, a major concern with bioplastics is that their production may compete with food production and increase land and water use. Biocomposites, however, may utilize natural fibers from streams that currently have no food use, such as wood fibers, or by-products from food production (Mohanty et al., 2018). Furthermore, adding natural fibers, which are biodegradable by nature, may enhance the biodegradability of the full material compound in natural environments (Shanmugam et al., 2021). Moreover, the bio-based fillers may improve the properties of the plastic (Mahmud et al., 2021; Sanjay et al., 2018), which could possibly address the performance issues of some bioplastics. Finally, as bioplastics in general are considered more expensive, introducing low-cost fillers to the material as a biocomposite could also reduce the costs of increasing bio-based content to plastics (Shanmugam et al., 2021).

Table 4: Potential solutions to bioplastic challenges by biocomposites

Challenges of bioplastics	**Potential solutions by biocomposites**
• Bio-based raw materials may compete with food production. • May have significant impacts on land and water use. • Biodegradability generally requires industrial composting. • Poorly managed biodegradation may have negative environmental impacts. • Mechanical properties are generally inferior to conventional plastics. • Bioplastics have high production costs which limit competitiveness.	• Increase bio-based content via utilizing natural fiber materials that currently have no food use and are side-streams. • Introducing natural fibers may enhance the biodegradability of the material altogether. • Bio-based fillers may improve the properties of the material. • Introducing low-cost fillers may reduce the cost of material.

Naturally, biocomposites also have challenges that limit their adoption. Biocomposites would need to compete with conventional plastics with identical or even better characteristics (Manu et al., 2022). However, they are often not able to deliver such benefits due to their various technical challenges, including the unpredictable durability of the material, and the inconsistency, and poor thermal and moisture sensitivity of the natural fiber fillers (Mahmud et al., 2021; Manu et al., 2022). In addition, the supply chains for bio-based fillers are by nature complex and vary by source (Mohanty et al., 2018). Nevertheless, there are some sectors where the use of biocomposites has been promising, such as in automotive, construction, furniture, electronics, and medical applications (Mahmud et al., 2021; Manu et al., 2022; Mohanty et al., 2018).

As noted by Shanmugam et al. (2021), most research on biocomposites has been technical and oriented towards material science. Although some lifecycle assessment (LCA) studies are available on the environmental impacts of biocomposites (e.g., Civancik-Uslu et al., 2018; Haylock & Rosentrater, 2018; Kamau-Devers & Miller, 2020), there seems to be rather limited studies with a holistic or systemic perspective regarding the role that biocomposite materials may have in the overall sustainability of the plastic economy. Against this background, this study aims to increase understanding in this area from a more holistic perspective.

2.3 Circular economy

This subchapter introduces the concept of the circular economy. Firstly, the background of the concept is discussed, and the core objectives and principles of circular economy are highlighted. Then, the chapter outlines how circular economy is employed in practice with the notion of circular strategies.

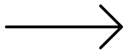
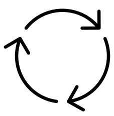
2.3.1 Background of the circular economy

During recent years, the concept of the circular economy (CE) has gained attention and importance amongst academia, industry, and policymakers (Geissdoerfer et al., 2017). The concept has mainly emerged as a solution to address the problems of the prevalent linear economy (Ellen MacArthur Foundation, 2013). In the linear economic model, resources are extracted from the natural environment, processed into products using energy and labor, and sold to consumers who dispose of the products after usage when they no longer serve their purpose (Ellen MacArthur Foundation, 2013; Murray et al., 2017). This linear way has been the default model for a major part of the industrial age (Ellen MacArthur Foundation, 2013).

In recent decades the problems related to the linear economic model have gathered more and more attention. Firstly, the linear economy is mostly based on extracting resources from the environment, which, combined with the exponential growth of economic activity during the past few centuries, has contributed to accelerated depletion of natural resources (Ellen MacArthur Foundation, 2013; Schandl et al., 2018). Secondly, the current global crises regarding climate change and loss of biodiversity have been acknowledged to originate from the current polluting and wasteful economy (Ellen MacArthur Foundation, 2021a, 2021b). The linear economy largely relies on fossil-based resources which create greenhouse gases that heat the planet (Ellen MacArthur Foundation, 2021a; Rockström et al., 2009; Shogren et al., 2019). Thirdly, the disposal of used products has created a major global waste problem, with used products piling up in landfills or natural environments (Ellen MacArthur Foundation, 2013; Geyer et al., 2017). In general, the linear system relies on abundant reservoirs of materials and energy, which increasingly contradicts with the planetary boundaries acknowledged today (Ellen MacArthur Foundation, 2013; Rockström et al., 2009).

An overarching problem in the linear model can be generalized as the waste of resources and value in different stages of the system, which is an inherent feature of the structure of the current economy (Ellen MacArthur Foundation, 2013). To turn the situation around, the circular economy has emerged as a potential solution to transition towards an economy that would be more sustainable (Murray et al., 2017). Ideally, a circular economic system is envisioned to have zero net effect on the environment and would potentially even restore damage done to the environment. It would create as little waste as possible in production systems and would overcome the inefficiency of resource use and the depletion of natural resources. (Ellen MacArthur Foundation, 2013; Murray et al., 2017) The general aim is to decouple economic growth from deteriorating the state of the environment: to create more societal, environmental, and economic value, while simultaneously reducing, avoiding, and negating the loss of value and creation of waste (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017; Murray et al., 2017). The main differences between the linear and circular economic models are summarized in Table 5 below.

Table 5: Summary of differences between linear and circular economic models

 Linear model	• Economic model based on extraction, use and disposal. • Inherently wastes resources and value. • Related to issues of depleting natural resources, accelerating climate change and biodiversity loss, and increasing the global waste problem.
 Circular model	• Economic model that focuses on circulation of resources and materials within the economy. • Minimizes waste through redesigning the economic system. • Aims to decouple economic activities and growth from negative environmental effects.

Although the CE concept has risen in attention and its development is seen important (Reike et al., 2018), in research its definition has not been entirely coherent (Kirchherr et al., 2017). A much renowned definition was formulated by the Ellen MacArthur Foundation, who define the circular economy as “an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.” (Ellen MacArthur Foundation, 2013, p. 7). Murray et al. (2017) define CE as “an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being" (Murray et al., 2017, p. 377). Geissdoerfer et al. (2017) define CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al., 2017, p. 766). As simply put by van Buren et al. (2016), the "focus point in a circular economy is to not unnecessarily destroy resources" (van Buren et al., 2016, p. 3).

The definitions of CE differ in emphasis but share some common ground. Firstly, CE relates to the structure of the *system*, meaning that circular economy emphasizes a systemic lens rather than just focusing on individual actors (Ellen MacArthur Foundation, 2013). Secondly, it connects to the *design* of the economic model within the system, bringing focus into how the structures, processes, inputs, and outputs within the economic model are designed and managed in a way that the system and its parts contribute to the prevention of resource loss (Ellen MacArthur Foundation, 2013; Murray et al., 2017). Thirdly, many definitions consider the notion of being '*restorative*' or '*regenerative*', highlighting that the circular economy not only aims to prevent value and resource loss but also aims to repair damage already done (Murray et al., 2017). Finally, CE is often described by various *circular strategies*, such as reduce, reuse, or recycle, which are practical implementation approaches that aim to close material and product loops, improve resource efficiency and reverse resource loss (Blomsma & Tennant, 2020; Kirchherr et al., 2017; Reike et al., 2018).

Behind the development of circular economy, there has been a variety of related streams of thinking that have shared the idea of closed loops (Geissdoerfer et al., 2017). According to several authors (e.g., Blomsma & Brennan, 2017; Murray et al., 2017; Reike et al., 2018), particularly influential to the development of these streams of thinking was an essay by the economist Kenneth Boulding, "The Economics of the Coming Spaceship Earth" in 1966. In the essay, Boulding (1966) notes that earlier human civilizations have thought to be living in a world with apparently limitless resources. With the humankind getting more aware of the boundaries of the planet, he notes that "the closed economy of the future might similarly be called the 'spaceman' economy, in which the earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system" (Boulding, 1966, pp. 7–8). According to Geissdoerfer et al. (2017), the circular economy has later evolved by incorporating features and concepts from various theoretical influences, such as cradle-to-cradle (McDonough & Braungart, 2002), performance economy (Stahel, 2010), regenerative design (Lyle, 1996), industrial ecology (Graedel & Allenby, 1995), and the blue economy (Pauli, 2010). In general, CE is grounded in the study of non-linear systems, particularly biological ecosystems, where different resources circulate naturally in different cycles of the biosphere (Ellen MacArthur Foundation, 2013).

Clearly, CE is gradually gaining more and more attention and becoming a goal to which societies aim to transition towards. This can be seen for instance in the European Union with the circular economy action plan (European Commission, 2020) as well as in the presence of circular economy in the five-year plans of China (Murray et al., 2017). However, to this end circular economy has not been implemented widely yet, or the implementation has mostly been fragmented and partial (Ritzén & Sandström, 2017). Therefore, the concept is to a degree still theoretical, although elements of it can be seen in the current economic reality.

2.3.2 Core objectives and principles of the circular economy

As discussed, the concept of circular economy aims to address issues of the linear economic model. To overcome the current problems, the CE concept mostly seeks improvements in three core dimensions: material productivity, preservation of value, and reduction of waste. In CE thinking, it is considered that focusing on improving these would lead to positive environmental and economic outcomes, such as decreasing the depletion of natural resources through limiting extraction, and decreasing the creation of harmful waste and pollution, while maintaining economic growth (Ellen MacArthur Foundation, 2013; Murray et al., 2017).

Firstly, circular economy aims to improve material and resource productivity which would decrease the need to extract virgin resources for production. *Material* or *resource productivity*, sometimes also material or resource *efficiency*, refers to how much economic output is gained per used material or resource input (Steinberger & Krausmann, 2011). Material extraction from the natural environment has significantly increased during economic development, as material-intensive production and lifestyles have persisted in high-income countries (Schandl et al., 2018). In CE thinking, this increase in primary material extraction usage is an inherent feature of the linear economy, which requires a major change for it to be decoupled from economic growth (Ellen MacArthur Foundation, 2013). The central idea in CE is, then, that by improving the circulation of materials and products by closing various loops, materials and resources may circulate longer in the economy and create more economic value per unit of material or resource (Blomsma & Brennan, 2017; Ellen MacArthur Foundation, 2013). This has opportunities in both creating more value as well as decreasing the need to extract virgin materials, which would reverse the depletion of natural resources as well as decrease other environmental harm (Ellen MacArthur Foundation, 2013; Scott et al., 2019).

Secondly, CE thinking particularly considers the preservation of value. In general, production processes input various factors of production, including the valuable resources and materials extracted from the environment as well as energy and labor inputs. The output of these processes are various products that then have embedded value in them. According to Reike et al. (2018), in the traditional linear economy, this embedded value is mostly lost as used products are disposed of. In contrast, however, circular economy notes that, in fact, there exists residual value in products after usage and at least a part of that value may be recovered instead of simply losing the value (Reike et al., 2018). Moreover, the implementation of circular economy may also be seen as a value creation opportunity, as many circular practices in industrial systems may in fact create additional value in comparison to linear practices (Ellen MacArthur Foundation, 2013). In general, value is seen in broad terms as not purely economic value, but also environmental and societal value (van Buren et al., 2016).

Thirdly, the resource and value loss in the current take-make-dispose economy is usually seen as waste (Ellen MacArthur Foundation, 2013). For instance, disposing products after short uses is seen to create waste as the value embedded in the product as well as the used resources are lost, rather than recovering the product or parts of it back to use. Thereto, an overarching goal in implementing circular economy is to reduce waste in the economic system (Blomsma & Brennan, 2017; Ellen MacArthur Foundation, 2013; Kirchherr et al., 2017).

Achieving improvements in material productivity, preserving more value embedded in products and materials, and reducing waste can be seen as central objectives of the circular economy (Blomsma & Brennan, 2017; Ellen MacArthur Foundation, 2013; Kirchherr et al., 2017; Reike et al., 2018). To reach these objectives, the CE is based on some central principles. These principles and the objectives are summarized in Figure 5 below.

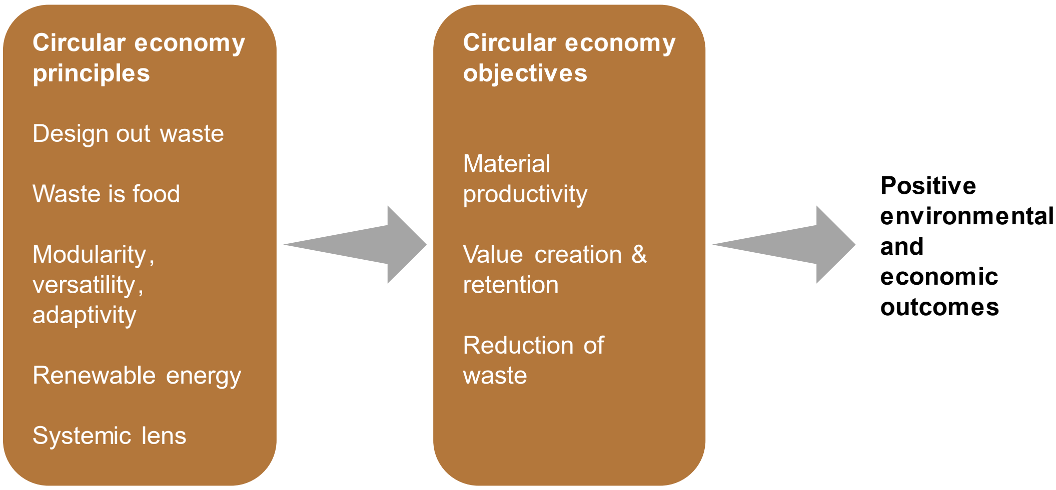


Figure 5: Summary of the principles and objectives of circular economy

Firstly, it is considered in CE that the economic system should be constructed so that all waste is designed out (Ellen MacArthur Foundation, 2013; Murray et al., 2017). Here, a distinction is often made between materials that are either biological or technical, which should have their own cycles or flows (McDonough & Braungart, 2002). Biological materials should circulate in a safe form back into the biosphere, whereas technical materials should circulate at high quality in their own cycles without reaching the biosphere (Murray et al., 2017). The circular economic system should then be designed so that all materials are purposefully designed to fit either a biological cycle or technical cycle, which would prevent the creation of waste materials not belonging to either cycle (Ellen MacArthur Foundation, 2013). In addition, a central design logic is that waste of some part of the economic system is food to some other part (Ellen MacArthur Foundation, 2013). This notion encompasses the idea of circulation or closing loops, which is a central part of the circular economy (Ritzén & Sandström, 2017).

Furthermore, in contrast to the logic of aiming to maximize throughput of production systems present in the linear economic model, the circular economic model emphasizes that economic systems should rather be designed prioritizing modularity, versatility and adaptivity (Ellen MacArthur Foundation, 2013). Then the economic system may be more resilient. Moreover, in CE thinking the current role of fossil energy is acknowledged as harmful, and the economic model should be then designed to rely on renewable energy sources (Ellen MacArthur Foundation, 2013). Finally, a central principle in designing the system is to emphasize a systemic lens, to prevent suboptimizing some parts of the economic system (Ellen MacArthur Foundation, 2013; Murray et al., 2017).

Although CE is mainly seeking to improve the environmental effects of the economic systems, implementing circular practices may also make economic sense. According to the Ellen MacArthur Foundation (2013), the CE may create economic value by saving costs in production when products and materials are reused, or loops are closed allowing production systems to use cheaper waste resources. In addition, by lengthening the lifetime of products the products may create more value as they are used longer (Ellen MacArthur Foundation, 2013). The overarching logic is, that in a circular economy, the economic growth would no longer be achieved by producing more, but by keeping products and materials available for consecutive usage (Ritzén & Sandström, 2017).

2.3.3 Circular strategies

In practice, the implementation of circular economy revolves around the employment of various *circular strategies* within industrial systems (Blomsma & Tennant, 2020). These strategies entail implementation patterns in industrial systems which focus on increasing the circulation of materials, resources, and products, and decreasing waste (Blomsma & Brennan, 2017). Although the strategies themselves are not necessarily novel (Reike et al., 2018), their involvement under the CE umbrella has brought attention into how such strategies may facilitate additional value extraction and reduce value loss and destruction (Blomsma & Brennan, 2017).

Circular strategies are often described with different 'R-frameworks' or 'R-imperatives'. These refer to various strategies starting with the letter R, such as 'reduce', 'reuse' to 'recycle' (Blomsma & Brennan, 2017; Kirchherr et al., 2017; Reike et al., 2018). According to Potting et al. (2017), the R-strategies may be classified into three broad categories: strategies that aim for useful application of materials in products after usage, strategies that aim to extend the lifespan of a product and its parts, and strategies that aim for smarter product use and manufacturing. Strategies identified within each category are listed in Table 6.

Recycling and recovery are the main strategies in aiming for useful applications of materials after usage. In efforts of promoting the circular economy, recycling is perhaps the most investigated and employed strategy (Kirchherr et al., 2017). According to Reike et al. (2018), recycling generally means processing mixed streams of wastes or discarded products using various technologies with the aim to capture pure materials. Recycled materials do not then maintain any of the structure of the original product since only the material is recovered (Reike et al., 2018). Recycled materials can have a lower quality than the original, which is the case in so-called downcycling, or the material may ideally be brought to a level of quality that equals a virgin material (Blomsma & Tennant, 2020). Recovery, on the other hand, does not typically aim for recovering materials but rather only the embedded energy in materials through incineration and production of energy (Potting et al., 2017; Reike et al., 2018). Recovering the energy in materials is still considered preferable over merely discarding products or materials (Potting et al., 2017).

Secondly, there are many strategies that aim to extend the lifespan of products or their parts. After use, if products are in good shape and still fulfil their functionality, they may be simply reused by other consumers as second-hand products (Reike et al., 2018). However, if the condition of the product is inadequate, it may be brought back to working condition through repair, or it may be remanufactured so that some parts that are in good condition are used in the production of a new product of the same function (Potting et al., 2017; Reike et al., 2018). If a product is outdated, it may be brought to modern condition through refurbishment (Potting et al., 2017). Finally, a product may be also repurposed to serve in some other functionality (Reike et al., 2018). The mentioned strategies essentially maintain the structure of the product and aim through different approaches to prolong their service lives (Blomsma & Tennant, 2020; Reike et al., 2018).

In the more innovative end of circular strategies are strategies where a smarter product use and manufacturing system is pursued. Ultimately, the circular economy may ideally be able to redesign industrial systems so that the use of some materials is totally prevented, i.e., their function is made redundant (Potting et al., 2017). Such 'refuse' strategies may be also seen to encompass the efforts of consumers to buy and consume less in general, as part of a less material-intensive lifestyle (Reike et al., 2018). Within smarter product use and manufacturing, there may also be innovative new business models that rethink the current economic system and generally reduce the consumption of products, such as through sharing economies (Potting et al., 2017; Reike et al., 2018). An increased efficiency in production may also be pursued, which allows to reduce overall material consumption (Potting et al., 2017). These strategies are more preventive measures, whereas the other previously mentioned aim for reutilization of materials and resources (Reike et al., 2018).

In terms of circular economy, a hierarchy may be established between the different strategies. According to Potting et al. (2017), strategies that aim for smarter product use and manufacturing and eliminating production altogether are considered more 'circular' than strategies that merely aim to recover energy or materials. As a rule of thumb, the more circular the strategies are, the fewer natural resources they consume and the less environmental pressure they create (Potting et al., 2017). This idea of the degree of circularity is illustrated as the arrow in the left-hand side of Table 6, which puts the different strategies on a scale of different degrees of circularity. Reike et al. (2018), on the other hand, note that shorter and longer loops may be identified within different circular strategies, and the length of the loop affects the extent that value is retained from products. For instance, material recycling or energy recovery retains less of the embedded value in the product after use than remanufacturing or repairing, where more embedded value in the product is retained. Therefore, to facilitate more value retention within the circular economy, shorter loops should be preferred over longer loops (Reike et al., 2018).

Table 6: Categorization of circular strategies (Adapted from Potting et al., 2017)

Circu-larity	**Strategies that aim for/to...**	**Strategies**	**Approach**
↑	smarter product use and manufacturing	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product.
		Rethink	Make product use more intensive (e.g., through sharing products or by products that are multi-functional).
		Reduce	Increase efficiency in product manufacturing or use by consuming fewer natural resources and materials.
	extend the lifespan of product and its parts	Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its function.
		Repair	Repair and maintenance of defective product so it can be used in its original function.
		Refurbish	Restore an old product and bring it up to date.
		Remanufacture	Use parts of discarded product in a new product with the same function.
		Repurpose	Use discarded product or its parts in a new product with a different function.
	useful application of materials	Recycle	Process materials to obtain the same or lower quality.
		Recover	Incineration of materials and recovering embedded energy.

2.4 The circular economy of plastics

This chapter integrates the context of plastics with the concept of circular economy. The contemporary possibilities for circular practices within the plastic economy are discussed, and a connection is made to how the whole plastic economy may contribute to environmental sustainability.

2.4.1 Background of the circular economy in the plastic context

Currently, plastics are produced and used following mostly a linear model of production and consumption. Plastic production is based on extracting raw materials, mostly from fossil-based non-renewable sources (Palm & Svensson Myrin, 2018). Although the use of plastics does create value in substituting more harmful materials, their use still for the most part follows a single use approach (Ellen MacArthur Foundation, 2017). After use, most plastics are merely disposed of, which causes many environmental problems (Geyer et al., 2017). As during the recent years these environmental problems have been increasingly acknowledged, the plastic industry has started to shift towards circular economy as a solution to deal with the environmental issues of the current linear model, by mostly increasing the amount of plastic that is reused or recycled back into the system (European Commission, 2018; Plastics Europe, 2022b).

Conventionally, after plastic materials are used, there are three possible pathways. Firstly, plastics may be destroyed thermally by incinerating them, where the embedded energy in the material is often recovered (Geyer et al., 2017). By incineration, the volume of plastic waste is greatly reduced, and the embedded energy may be utilized through recovery, but burning plastics releases carbon dioxide to the atmosphere along with toxic heavy metals and noxious gases (Acquavia et al., 2021). The second option is to discard the material, either to a contained environment such as a landfill, or to an uncontained open dump or littered to the nature (Geyer et al., 2017). This approach, naturally, is the cause of the major plastic waste problem on the planet (Ellen MacArthur Foundation, 2017). To avoid the undesirable outcomes of accumulating waste plastics or releasing emissions, the third pathway for plastics is to use them again within the plastic economy (Geyer et al., 2017). By employing different circular practices, the material can have consecutive usages, which could limit the creation of waste and the need for virgin inputs (Ellen MacArthur Foundation, 2017). Although there are many possible circular strategies that may be applied, it seems that recycling is the most important area in industry developments and public policy (European Commission, 2018; Plastics Europe, 2022b).

Against this background, the following sections discuss and elaborate what recycling encompasses in the plastic context. Especially, the different available recycling technologies and their characteristics are discussed. Furthermore, waste management is discussed as an important factor in facilitating recycling. However, it is recognized that there also exist other alternative approaches for the disposal of plastics beyond the conventional pathways, some of which are further discussed. Finally, it is discussed how the plastic economy can on a systemic scale have an impact on environmental sustainability.

2.4.2 Plastic recycling technologies

Generally, recycling means processing waste streams to capture nearly pure materials for secondary use (Reike et al., 2018). In the context of plastics, there are essentially two main groups of recycling methods: mechanical recycling and chemical recycling (Fredi & Dorigato, 2021; International Energy Agency, 2018). The capabilities of these two groups of recycling technologies differ from each other, such as with the kinds of plastic waste they can deal with and the quality of their outputs. A summary of the key advantages and disadvantages of the two recycling technologies is provided in Table 7.

Currently, the most employed method for recycling plastics is mechanical recycling (Plastics Europe, 2022b). In this approach, waste plastics are processed mechanically back to polymers in such a way that their chemical structure stays intact (International Energy Agency, 2018). Typically, plastics are sorted from waste streams by type, shredded to small fragments, washed, and re-melted back into pellets or granulates that can then be used in compounding plastic material for new plastic products (Plastics Europe, 2022b; Shanmugam et al., 2021).

Mechanical recycling is generally considered as a low-cost recycling method (International Energy Agency, 2018; Shanmugam et al., 2021). Moreover, it requires relatively simple technology and consumes relatively less energy (Fredi & Dorigato, 2021). However, a key challenge in the mechanical approach is that it reduces the quality and properties of the material, as the processing steps damage the polymer chains in the plastic (Plastics Europe, 2022b). Therefore, there is a maximum number of cycles that plastic material may be mechanically recycled, and typically before using recycled material in new products, virgin plastic must be added to increase the quality of the material (Shanmugam et al., 2021). Moreover, the quality of the recycled material is highly dependent on the quality of the input waste material, meaning there is much importance in how well the recycling system can identify and sort high quality and pure plastic materials from the waste streams before they are mechanically recycled (Fredi & Dorigato, 2021; Shanmugam et al., 2021). Finally, in mechanical recycling different impurities stay in the recycled material, and for instance different chemical additives cannot be removed from the material (International Energy Agency, 2018). One category of such additives which cannot be removed are colorants, and therefore mechanically recycled plastics made from mixed-color plastic streams are limited to gray or black colors as different colors are mixed (International Energy Agency, 2018; Palm & Svensson Myrin, 2018). Given the overall reduction of quality and limitations in properties, the use of mechanically recycled plastics is often limited to inferior applications than their original functions, which often means downcycling (Fredi & Dorigato, 2021; International Energy Agency, 2018). One central restriction, especially in the packaging context, is that recycled material can rarely be used for food contact due to the danger of contaminants (Shogren et al., 2019).

The other main approach for recycling is chemical recycling. This category encompasses more novel technologies, which are not utilized on a large scale yet but are strongly invested on (Plastics Europe, 2022b). Contrary to mechanical recycling, the idea is to break down the plastic material back to its building blocks by utilizing different chemical reactions (International Energy Agency, 2018; Shanmugam et al., 2021). As an output are different chemicals, such as monomers or oligomers, that may be reintroduced into the production chain and polymerized again (Fredi & Dorigato, 2021; Plastics Europe, 2022b). The actual process of chemical recycling highly depends on the plastic type and the technology appropriate for breaking down the specific type of plastic, but the main methods utilized and investigated as chemical recycling are pyrolysis and solvolysis (Fredi & Dorigato, 2021). Pyrolysis, and related gasification, is conducted by heating the waste plastic in an oxygen-free environment, which degrades the polymer chains into less complex molecules, resulting in gases, liquid oils, and solid chars (Lamberti et al., 2020; Plastics Europe, 2022b). The gases and oils can then be used as a recycled feedstock in polymer production (Plastics Europe, 2022b). Solvolysis, on the other hand, is an umbrella term for different techniques where a solvent is used to depolymerize the polymer into monomers, including, for instance, hydrolysis, glycolysis, and alcoholysis (Fredi & Dorigato, 2021).

Chemical recycling is considered beneficial, because the technologies can produce recycled plastics that are as good quality as virgin plastics, and therefore plastics may be chemically recycled, in theory, for indefinitely many times, which is not the case with mechanical recycling (International Energy Agency, 2018; Lamberti et al., 2020). Moreover, different colorants and other contaminating additives are removed from the material in the chemical processes, so the chemically recycled plastics are much less limiting for their applications (Shanmugam et al., 2021). Furthermore, chemical recycling technologies can use lower quality, more mixed, and contaminated inputs, which makes it a more robust method for waste streams that would otherwise be difficult to recycle mechanically (Fredi & Dorigato, 2021; Plastics Europe, 2022b). However, chemical recycling requires more complex industrial equipment, which makes it more capital-intensive, more costly, and more energy-consuming than mechanical recycling (Fredi & Dorigato, 2021; International Energy Agency, 2018; Shanmugam et al., 2021). As the processing in chemical recycling breaks the material down back to monomers, it may lose more value in the material as more further processing, for instance polymerization, is required to get it to the same point in the production chain as material from mechanical recycling, although the quality is higher than mechanically recycled (Plastics Europe, 2022b).

Table 7: Summary of the advantages and disadvantages of plastic recycling by mechanical and chemical technologies

	Mechanical recycling	**Chemical recycling**
Advantages	• Low-cost recycling method. • Requires simple technology. • Consumes less energy.	• Can produce recycled material of as high quality as virgin plastics. • Can be recycled for an indefinite number of cycles. • Can remove additives from the material. • Can use lower quality, mixed and contaminated input streams.
Disadvantages	• Reduces quality of material. • Limited number of cycles. • Sensitive to quality of inputs and requires sorting before processing. • Cannot remove additives and impurities from material, such as colorants. • Typically returned to inferior applications.	• Requires complex equipment and is capital-intensive. • More costly method. • Consumes more energy. • Introduces recycled material further upstream in the value chain.

Since the two groups of recycling technologies have their own benefits and drawbacks, it is likely that both mechanical recycling and chemical recycling will have a role in the plastic circular economy as they complement each other (Plastics Europe, 2022b). Although chemical recycling could in theory make a fully circular plastic economy possible, it will require more energy and have more costs, making the economics of recycling more difficult to compete with virgin fossil-based plastics production (International Energy Agency, 2018). Mechanical recycling is then still needed, albeit with its inherent boundaries. Furthermore, recycling, in general, can be seen beneficial only if it can displace production of virgin plastics, which may be uncertain especially given the quality issues of mechanically recycled plastics (Geyer et al., 2017).

2.4.3 Plastic waste management

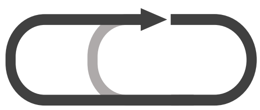
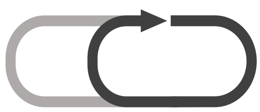
As discussed in the previous section, plastic recycling may be conducted through using mechanical or chemical recycling technologies, of which the former is the most used, cheaper, and less energy-consuming method. However, the issues of quality in mechanical recycling highly depend on the quality of input streams (Fredi & Dorigato, 2021). To this end, the practices of waste collection, sorting and management have a significant importance on how recycling may be performed at a high quality (Plastics Europe, 2022b). In this area, an important factor is whether plastics are collected in a mixed or separate approach, and this aspect is discussed next.

According to Plastics Europe (2022b), in Europe roughly half of collected post-consumer plastic waste is collected through mixed collection, and the other half through separate collection schemes. From mixed collection, plastic wastes need extensive sorting to acquire fractions good enough for mechanical recycling (Fredi & Dorigato, 2021; Plastics Europe, 2022b). Identifying and sorting plastics may be performed either manually using markings and labels, or automatically based on density differences or optical systems such as near-infrared (NIR) techniques (Fredi & Dorigato, 2021). Nevertheless, there is a high risk of plastics being contaminated with other types of waste, such as organic waste, which disturbs the subsequent recycling processes and affects the quality of recycled materials that may be obtained (Plastics Europe, 2022b). Often, the poor-quality recycled material ends up in lower value and less demanding applications (International Energy Agency, 2018). Moreover, the issues in sorting of mixed waste streams make the processes rather expensive, which has limited recycling rates in Europe at only around 30% on average (Acquavia et al., 2021).

However, to prevent extensive sorting and to limit contamination, plastic waste collection could adopt separate collection approaches, if feasible (Plastics Europe, 2022b). If the system can obtain plastic waste fractions that are of high-quality, and the history of the material is known, it may be possible to mechanically recycle plastic to a near similar quality as virgin plastic, and to apply the high-quality recycled material in applications of as high value as the original, instead of downcycling (Fredi & Dorigato, 2021; Lamberti et al., 2020). In fact, according to Plastics Europe (2022b), plastic recycling rates may be even 13 times higher if the waste is collected separately.

Against this background, improving recycling in the plastic context is clearly not just dependent on the recycling technologies themselves, but rather also on the design of the collection system. To this end, this thesis argues that a distinction can be made within the plastic recycling system into two main models of the collection and recycling system: large loops and small loops. The main idea of both loops is summarized in Table 8 below.

Table 8: Large and small loops in plastic waste collection and recycling

 **Large loop**	• Models where plastic waste is collected in a mixed way. • The mixed waste stream requires extensive sorting to be suitable for recycling. • May be easier for consumers since waste sorted later automatically. • Logistics may be more efficient as optimized for large amounts of waste. • Plastic waste is likely to be contaminated, which leads to low-quality recycled material and high rates of rejection to incineration.
 **Small loop**	• Models where plastic waste is collected with a separate approach. • Extensive sorting is avoided as the stream is controlled. • Knowing the history of the material allows it to be mechanically recycled at high quality. • There may be logistic issues. • May be implemented with, e.g., deposit-refund or take-back schemes.

The loops essentially describe two operational models through which collection of plastic waste for recycling may be organized. Large loops essentially encompass the mixed approaches for plastic collection, where waste plastics are obtained from a mixed waste stream through extensive sorting. A large loop approach may be easier for consumers since there is less need to sort plastics in a household, and the logistics may be carried out more efficiently along with collection of municipal waste and processing in optimized and centralized facilities. However, contamination is likely, leading to low-quality recycled material and significant rejection streams to other disposal routes such as incineration (Fredi & Dorigato, 2021).

The small loop model, however, describes operational models where plastics are collected in a separate approach, so that the history of the material may be known and the waste stream more controlled. Such approaches may also be called closed-loop recycling or primary recycling (Fredi & Dorigato, 2021; Lamberti et al., 2020). By knowing the history of the waste material and less contamination, this could lead to a higher chance that mechanical recycling may be utilized at a high quality (Rosenboom et al., 2022). However, there may be issues with logistics, which would need to be designed accordingly, such as with deposit-refund or take-back schemes. An example could be the PET-bottle deposit-refund schemes in Nordic countries, which are able to reach recycling rates as high as 85-95% with a system resembling a small loop (Milios et al., 2018).

2.4.4 Alternative disposal strategies for plastics

It is important to note that recycling may only delay, rather than fully avoid, the final disposal of plastic materials by some other means (Geyer et al., 2017). Because neither mechanical nor chemical recycling can recover all the plastic material in high-quality from the waste streams (Fredi & Dorigato, 2021), there will always be residual waste that needs alternative disposal (Meys et al., 2022). For these end-of-life strategies, four main alternative approaches are identified: landfilling, energy recovery, biodegradation, and conversion to other carbon products. These are elaborated next and summarized in Table 9.

2.4.4.1 Landfilling and energy recovery

As discussed previously in 2.4.1, before recycling, landfilling and incineration have been the traditional routes for disposing plastic wastes. Over the history of using plastics, landfilling has been the default and most utilized final disposal route for plastics (Palm & Svensson Myrin, 2018). According to a study by Geyer et al. (2017), almost 80% of all plastic ever produced has been landfilled or littered to the nature. This, again, has led to the major global plastic waste problem (Ellen MacArthur Foundation, 2017).

The other main route, incineration, has historically been utilized for only about 12% of plastics as a disposal route (Geyer et al., 2017). Nowadays, however, incineration and energy recovery have a much larger role, as for instance in Europe about 42% of plastic waste in 2020 were used for energy recovery (Plastics Europe, 2022b). Incineration and energy recovery may be seen positive since it allows the high energy content in plastics to be captured (Andrady & Neal, 2009). Although recovering energy is one of the circular strategies commonly identified (see Table 6 in 2.3.3), it still produces harmful emissions and loses the effort and labor that have been used into producing the plastic material (Acquavia et al., 2021; Ellen MacArthur Foundation, 2017). Nevertheless, it is likely that energy recovery and landfilling will have a role in the future, at least for some more challenging streams of waste.

2.4.4.2 Biodegradation

Beyond the more traditional pathways for disposing of plastics, there are some more novel ways also being investigated. One such route is biodegradation, which was already discussed previously in 0 in conjunction with bioplastics. Adopting biodegradable plastics could be seen as an alternative approach for waste disposal since biodegradable plastics offer biological degradation or composting as a possible route for destroying the material (Fredi & Dorigato, 2021). In aerobic composting, microbial digestion and metabolic conversion transforms biodegradable polymers into CO_2, water, and other inorganic compounds in a rich soil that may be returned for agricultural purposes (Rosenboom et al., 2022; Shogren et al., 2019). On the other hand, through anaerobic digestion biodegradable plastics may be converted into biogas, essentially methane, which may be used for energy purposes (Fredi & Dorigato, 2021; Shogren et al., 2019). However, burning such gas will result in GHG emissions (Rosenboom et al., 2022). Biodegradability, in general, may also be seen as organic recycling, in which the CO_2 that is released to the atmosphere (through composting or burning biogas) is again captured by plants through photosynthesis, and the plants may then be used in the production of new bio-based materials (Rosenboom et al., 2022; Shanmugam et al., 2021).

Biodegradability has been especially developed with the purpose of mitigating the effects of plastic waste to the natural environment, so that plastic that leaks to the environment could have the capacity to degrade rather than persist and contaminate the environment (European Commission, 2018). However, most biodegradable plastics today require industrial composting, meaning that their degradability outside such environments may be rather limited (Ellen MacArthur Foundation, 2017; Lamberti et al., 2020). Moreover, even though biodegradable plastic would reach industrial composting along with other organic waste, there remains a high risk that plastics may be sorted out and incinerated since their degradation time may be substantially longer than for other organic waste (Rosenboom et al., 2022; Shogren et al., 2019). Another concern is behavioral since there is a risk that labeling plastic biodegradable could increase littering, although biodegradable plastic may not in fact degrade in the open environment (European Commission, 2018; Palm & Svensson Myrin, 2018). In addition, there are concerns about the compatibility of biodegradability and plastic recycling. Technically, biodegradable plastics may be recycled in a similar way as commodity plastics, but they would need to be separately processed (Fredi & Dorigato, 2021). If the separation is not managed properly, there are concerns that biodegradable plastics may contaminate other recycling streams of plastics (Shogren et al., 2019; Soroudi & Jakubowicz, 2013). In addition, as of currently, biodegradable plastics are still marginal in volume and represent new plastic types, which increases even further the heterogeneity of plastic waste streams and makes sorting more demanding, thus making it rather likely that biodegradable plastics will be rejected in recycling streams (Rosenboom et al., 2022). Finally, if biodegradable plastics are not recycled, the value embedded in the product from its production is essentially lost, similarly as in the incineration of plastics (Lamberti et al., 2020). Although there are many issues, biodegradability is still considered beneficial in some applications, especially in such where it is considered likely that the plastic material would leak into the environment (European Commission, 2018; Palm & Svensson Myrin, 2018).

2.4.4.3 Conversion to other carbon products

In addition to the currently utilized disposal methods of plastics, waste plastics can also be processed into various carbon products (Yaqoob et al., 2022). In recent years, an innovative solution to deal with plastic waste has emerged in the possibility of converting bio-based plastics into solid carbon products such as biochar (Igalavithana et al., 2022). Biochar, or biocarbon, is an amorphous material that is rich in carbon (Mohanty et al., 2018). It has various possible applications, such as in soil amendment to improve soil fertility in agriculture (Criscuoli et al., 2014), in wastewater treatment due to its high porosity (Singh et al., 2021), or in various industrial products such as construction (Schmidt et al., 2019). However, its environmental significance originates from the fact that producing biochar from biomasses is considered as one of the most promising negative emission technologies (Schmidt et al., 2019; Werner et al., 2018; Woolf et al., 2010). It is generally accepted that the growth of plants and their photosynthesis is the most efficient method to draw carbon dioxide away from the atmosphere (Schmidt et al., 2019). These biomasses, which then contain atmospheric carbon, may be processed by pyrolysis, which is a thermal treatment without oxygen, preventing the further decaying of biomasses (Woolf et al., 2010). As an output the process yields biochar, which is a stable form of carbon that may be stored in soil for hundreds of years (Criscuoli et al., 2014). In addition, the process yield bio-oils and gases that have alternative uses in energy or also storing carbon (Schmidt et al., 2019). This process is referred to as pyrogenic carbon capture and storage (PyCCS) (Schmidt et al., 2019; Werner et al., 2018).

The process of PyCCS as a negative emission technology has been primarily investigated with biomass inputs (Woolf et al., 2010). However, recently it has emerged also as a possible approach to deal with plastic waste (e.g., Igalavithana et al., 2022). Another example of a proposed PyCCS solution is to transform the plastic waste into products that substitute for fossil raw materials in steel production (Devasahayam et al., 2019). The production of biochar through pyrolysis is likewise possible from plastic waste as it is from biomasses (Singh et al., 2021). Approaches have also been developed where plastic waste is pyrolyzed together with biomasses in a co-pyrolysis process, which seems especially attractive for biochar production (Al-Rumaihi et al., 2022; Rathnayake et al., 2021). However, to constitute a truly negative emission, it may be determined that the plastic inputs should originate from bio-based plastics, which essentially store atmospheric carbon similarly as biomasses (Stegmann et al., 2022). The production of biochar from plastics seems viable since it utilizes pyrolysis, which is also one of the main technologies for the chemical recycling of plastics (Fredi & Dorigato, 2021). However, to this end plastic pyrolysis has been mainly tuned towards recycling, i.e., maximizing the yields of gases and oils from pyrolysis which may be utilized in new polymer production, rather than aiming to produce chars which seems nevertheless technically possible (Al-Rumaihi et al., 2022). Since biochar production from plastic wastes is still a novel and emerging approach, it still requires more investigation and is therefore the least mature option from the alternative disposal strategies discussed previously.

Table 9: Summary of alternative disposal approaches

Approach	Description
Landfilling	• Plastic waste discarded and collected to a landfill. • Historically the most employed disposal approach. • Likely to lead to plastic waste leakages to nature.
Energy recovery	• Plastic waste burned for energy use. • Allows the high energy content of plastics to be utilized. • Releases harmful emissions.
Biodegradation	• Biological degradation or composting as an alternative disposal method. • Applicable only for biodegradable plastics. • Aerobic composting transforms material into CO_2, water, and inorganic compounds in a rich soil, which can be used in agriculture. • Anaerobic digestion allows the capture of biogas from material, which may be used for energy. • Often biodegradable plastics require industrial composting.
Conversion to other carbon products	• Plastic waste may be processed to other carbon products. • One such approach is conversion with pyrolysis into biochar, which is a carbon-rich material. • Biochar may act as a long-term carbon storage.

2.4.5 Carbon capture and storage within the plastic economy

In the previous chapters, the circular economy of plastics has been discussed from the perspective of recycling and alternative final disposal strategies. However, it is imperative to adopt a systemic perspective to establish a meaningful relationship with these circularity practices in the plastics context and the environmental sustainability of the whole plastic economy (Ellen MacArthur Foundation, 2017). A practical approach to such system-level thinking would be to examine the circulation of carbon within the plastic economy. Such a perspective allows to examine the relationships and effects of the plastic economy system to the environment in a meaningful and concrete way.

As a potential model for systemically examining the circulation of carbon, Suh and Bardow (2022) offer a helpful thinking model. According to them, the issue of global climate change boils down to where in Earth's four main compartments carbon should be stored: in the atmosphere, biosphere, hydrosphere, or geosphere (Suh & Bardow, 2022). Although carbon circulates naturally between these segments, the problem of climate change is essentially that human activity has increased carbon stocks in the atmosphere and continues to do so (Rockström et al., 2009). Within this model, anything that may be considered to reduce the stocks of carbon in the atmosphere, or limit its increase there, may be considered beneficial in the efforts to counteract climate change (Suh & Bardow, 2022).

However, in addition to the four compartments, Suh and Bardow (2022) note that there also exists a fifth compartment, the 'technosphere'. This compartment includes all the human-made objects on Earth. Notably, all these objects may also act as carbon storage during their existence, and capture carbon away from the atmosphere. Since the mass of conventional plastic materials consists mostly of carbon, plastic materials that are in use or have not been otherwise destroyed may offer such a storage for carbon within the technosphere (Stegmann et al., 2022).

Examining the transfer of carbon between the technosphere and the other compartments is helpful to understand the systemic implications of plastic economy. To illustrate, as most plastics originate from fossil-sources, carbon is essentially taken from the geosphere, stored for a limited time in the technosphere as plastics are used and recycled only to a limited extent, and finally increasingly disposed of through incineration, which releases the carbon to the atmosphere. This transfer process of carbon illustrates the problem of the current linear operating model in the plastic economy, where carbon essentially moves from a stable state in the geosphere to the atmosphere where it heats the climate, and is difficult to be removed from there anymore.

In contrast, various authors have noted that, in an ideal scenario, it is possible for the whole plastic economy to operate as a carbon sink or a net negative emission, drawing carbon away from the atmosphere (de Oliveira et al., 2021; Stegmann et al., 2022; Suh & Bardow, 2022). There are a few requirements for this to occur. Firstly, the fossil-based feedstocks should be replaced with bio-based feedstocks, which through the photosynthesis of plants draw carbon away from the atmosphere to the biosphere, and further to the technosphere when plastics are produced from biomasses (Suh & Bardow, 2022). Secondly, by radically adopting circular economy practices, the service life of plastic materials may be extended, thus storing carbon in the technosphere either in repeating cycles of recycling or long-life plastic applications (de Oliveira et al., 2021; Stegmann et al., 2022). Thirdly, the final disposal routes which release carbon into the atmosphere should be avoided (Stegmann et al., 2022). Landfilling plastics might be seen beneficial in this perspective as it essentially creates a long-term storage for carbon, but it is nevertheless not considered environmentally desirable since it creates issues of contaminating natural environments with plastic waste (de Oliveira et al., 2021). For this, a possibility could be the pyrolysis processing into biochar that could provide a medium- to long-term storage for carbon in the biosphere or geosphere (Al-Rumaihi et al., 2022; Schmidt et al., 2019). Finally, significant to the global warming impact of plastics is also the current use of fossil energy in the various plastic processing stages, which would need to be replaced by using renewable energy instead (Stegmann et al., 2022; Zheng & Suh, 2019).

2.5 Synthesis of the background literature

As is highlighted in the background literature, plastics have become a critical material class in the modern economy due to their many advantageous properties (Andrady & Neal, 2009). Although they bring many benefits, the production, use, and disposal of plastics follow a linear economic model, which creates a multitude of negative environmental effects (Ellen MacArthur Foundation, 2017). To overcome these environmental impacts, two main developments have been identified: increasing the use of bio-based feedstocks and transitioning towards a circular economy of plastics.

Bioplastic materials have emerged as a potential class of plastics that may replace fossil-based plastics and be more environmentally friendly (Di Bartolo et al., 2021). However, there are issues with the competitiveness of bio-based plastics and the dangers of cannibalizing food production and increasing land and water use (Di Bartolo et al., 2021; Palm & Svensson Myrin, 2018; Rosenboom et al., 2022). An innovative class of materials labelled biocomposites has emerged as a potential material to replace conventional plastics and possibly having less disadvantages than other bioplastics (Mahmud et al., 2021; Sanjay et al., 2018).

The transition towards a circular plastic economy aims to counteract the main deficiencies of the current linear plastic economy. Two critical technologies, mechanical and chemical recycling, are identified as the prominent methods to recycle plastics, both with their own advantages and disadvantages (see Table 7). As recycling has its limitations, the plastic economy must also utilize different strategies for the final disposal of plastics, of which landfilling and energy recovery constitute traditional pathways (Geyer et al., 2017), and biodegradation or conversion to carbon products such as to biochar through pyrolysis are identified as more novel approaches (Al-Rumaihi et al., 2022; Fredi & Dorigato, 2021; Igalavithana et al., 2022).

Adopting circular economy practices has environmental benefits in limiting the need of virgin feedstocks, because the increases in the circulation of plastics allow consecutive usages of the material (Ellen MacArthur Foundation, 2017). However, the demand for plastics is expected to remain in a highly increasing trajectory, so the stock of plastics in use must increase (Geyer et al., 2017). For this reason alone, the system will need new virgin feedstocks even though a circular economy would be highly adopted (Palm & Svensson Myrin, 2018). These feedstocks should favorably be bio-based rather than fossil-based to limit the environmental impacts of plastic production. In addition, since the circular economy practices have their limitations and material may not be able to circulate forever, the plastic sector should also consider which disposal options for the materials are most beneficial from the environmental point of view. In fact, it may be possible for the sector to act as a net negative emission, but only under strict conditions where circulation is dramatically increased, disposal of plastics leads to long-term depositories of carbon, and feedstocks of new plastics are from bio-based sources (de Oliveira et al., 2021; Stegmann et al., 2022; Suh & Bardow, 2022).

As bio-based plastics are considered problematic, biocomposite materials may be an opportunity to increase bio-based content in plastics and increase sustainability of the plastic economy. Biocomposites have been, thus far, mostly investigated from a material technology point of view (Shanmugam et al., 2021). Previous research is, however, limited in a holistic perspective on how biocomposite materials may operate in the broader plastic economy that aims to move towards environmental sustainability especially by the adoption of circular economy practices. In this area, the thesis acknowledges a research gap that requires more understanding.

3 Research methodology

In the previous chapter, the thesis explored background literature to establish the context of the research. From past research literature, a research gap was identified in how biocomposite materials could deliver sustainability benefits and what their role could be in the plastic economy, which is undergoing a transition towards better environmental sustainability and circular economy practices. To create more understanding in this area, the research questions that this thesis study aims to answer were formulated to guide the research process (see 1.2).

In this chapter, the thesis explains the methodological approach employed in the research. Firstly, the chapter elaborates on the overall design and approach of the research study and justifies why the chosen methodology is appropriate for the research context. Moreover, the characteristics of the chosen case are discussed, and the research process is elaborated. In the second part, the chapter describes a conceptual approach that is utilized in modeling the main problem areas in the plastic economy and assessing the impact of biocomposite materials to the system. Thirdly, the chapter explains in more detail how the empirical data of the study was collected and how the data was analyzed to develop findings for the study. Finally, the chapter evaluates the methodological approach of the study and discusses potential limitations of the approach.

3.1 Research design and process

This thesis is an abductive qualitative research study that follows a single case study design. As described by Dubois & Gadde (2002), an *abductive* research approach is characterized by moving continuously between the empirical world and a theoretical modelling world. Reasoning and development of new knowledge is driven by combining insights from both theory and empirical data (Dubois & Gadde, 2002). In the abductive research process, the research focus and theoretical framework are constantly revised based on observations as matching between theory and reality is eventually sought (Dubois & Gadde, 2002).

The abductive research approach was chosen for this study based on the nature of the research context. To understand how biocomposite materials may contribute to sustainability and circularity in the plastic economy, it was first imperative to understand the operation of the plastic economy, various current solutions to improve sustainability, as well as the reasons why biocomposites are thought to be a sustainable material. These insights based on the literature review established the initial theoretical framework for the study. However, it was noted by the identified research gap that there is limited system-level understanding on how the biocomposite materials could provide sustainability benefits as part of a complex value chain system, and for this the abductive research approach combining both theoretical and empirical insights was deemed appropriate. Although Dubois & Gadde (2002) see an abductive research approach to focus on theory development, Ketokivi & Choi (2014) acknowledge that there might also be other purposes. In fact, this research might be more accurately described as *theory elaboration* since there is a general theoretical background but not sufficient understanding of the empirical context to formulate a testable hypothesis (Ketokivi & Choi, 2014). Most notably, this study aims to elaborate relationships between factors affecting sustainability and boundary conditions to how biocomposites may create sustainability benefits.

The research method chosen for this study is a *case study*. According to Yin (2009), a case study is a preferred strategy if the research can be characterized by the following elements: (1) the study aims to answer "how" and "why" questions; (2) the researcher cannot manipulate events in the research context; and (3) the focus is on a contemporary phenomenon within some real-life context (Yin, 2009). In this study, these characteristics are well fulfilled. The research questions of this study are formulated as *how* biocomposite materials could promote environmental sustainability and circular economy practices in the plastic context, which justifies the use of a case study method. The focus is also on contemporary phenomena, namely what is happening currently in the plastic sector, and the researcher does not have an ability to manipulate events in real-life, which rules out the possibility of using experimentation as a research approach. Furthermore, according to Yin (2009) a case study is appropriate when the boundaries of the investigated phenomenon and the context are not fully clear, which also characterizes this study to some extent.

Moreover, the study can be characterized as a *single case study*. As the single case, the thesis studies the plastic value chain in Finland. To study the whole value chain of plastics in an economic area as a case is justified by the nature of the research questions. The aim in the research is to understand how biocomposite materials act in a plastic value chain, not just in the level of a plastic product or a company, and how biocomposites can contribute to sustainability on a system level. Therefore, it is crucial to understand the larger picture of the value chain where different companies have different roles in creating value, and how they interact in relation to each other and the material choices. A single case of a plastic value chain is then chosen as an appropriate means to investigate the complexities within a value chain.

The Finnish plastic sector was chosen mainly based on access, but it also has characteristics that support it as a choice for a single case study. According to Yin (2009), a single case may be justified if the case is representative or typical. Generally, the Finnish plastic sector can be evaluated as a rather representative case among different plastic sectors in European countries (Plastics Europe, 2022a). However, the Finnish sector distinguishes from other European countries by having comparatively a rather low recycling rate recycling rate for plastics (21 % in Finland compared to European average 35%), but a very high rate of energy recovery as a disposal route for plastics (77% in Finland compared to European average 42%) (Plastics Europe, 2022a). Naturally, the European countries in general are more mature in plastic waste management and recycling than many countries outside Europe.

In addition to representativeness, Yin (2009) considers the uniqueness of the case to also be a rationale for justifying a single case. For investigating biocomposite materials, the Finnish plastic sector has some uniqueness compared to other countries. Finland has a large forestry sector and a large availability of forestry side-streams (Ministry of Agriculture and Forestry in Finland, 2023), which can be applied in biocomposite materials (Mohanty et al., 2018). Partly because having available side-stream resources from forestry, large Finnish forestry companies have brought biocomposite materials to the market using various side-streams as a raw material (Stora Enso, 2019; UPM, 2020). For this reason, the Finnish plastic sector represents as a case where the value chain actors have some experiences from biocomposite materials, which allows their impacts on the value chain and on the sustainability of plastic products to be investigated.

Because of the nature of the chosen case and the research objectives, the design of the study can be also characterized as an *embedded single case study* (Yin, 2009). Since the purpose is to understand the plastic value chain and the effects of biocomposite materials, the study seeks to understand perspectives from different kinds of actors in the value chain. In the plastic value chain, some companies create value by producing plastic materials and some manufacture plastic products or packages using plastic materials. The value chain actors also after the usage phases are important, namely the actors that contribute to the waste management and recycling of plastic waste. All these value chain actors have a role in how the plastic sector is structured and how the system operates with different materials and with different segments of plastic use. Against this background, the study is designed as an embedded single case study, which is appropriate when within the single case attention is also given to subunits of analysis (Yin, 2009). Within the single case of the Finnish plastic sector, there are multiple actors with different roles in the plastic value chain, and which have differing operating logics and perspectives to new materials. Understanding the role of biocomposite materials is then investigated from the perspective of different value chain actors. The choice of what value chain actors were considered in the analysis is further elaborated later in 3.3.

The case study approach may also be characterized as *explorative* (Yin, 2009). Existing knowledge of the specific topic is limited, which is why this study aims to explore how biocomposite materials could provide sustainability benefits in the practical plastic context. By increasing understanding in this area, this study aims to lay grounds for further research in the area.

Finally, the research approach of this study also includes elements of *design science*. According to Holmström et al. (2009), design science research is primarily aiming at discovery and problem solving rather than aiming to accumulate theoretical knowledge. It may be argued that the needed sustainability transition in the plastic context is an ill structured problem, where "*decision makers may not know or agree on the goals of the decision, and even if the goals are known, the means by which these goals are achieved are not known and requisite solution designs (e.g., technologies) to solve the problem may not even exist*" (Holmström et al., 2009, p. 67). This characterization of an ill structured problem fits well the problematics in the plastic context moving towards sustainable practices. The approach in this study is then to consider biocomposite materials as a solution design that could offer a solution to the sustainability transition of plastics. The study then focuses on evaluating biocomposites as a solution based on theoretical and empirical insights.

The structure of the research process is illustrated below in Figure 6. The process started with an initial literature review, which provided a basis for formulating the research questions and objectives and to understand the plastic economy context. After formulating the objectives and focus of the research, the research process divided into two parallel streams: conducting a more comprehensive literature review and the empirical data collection. An iterative approach was adopted such that the research focus and research questions were iterated based on initial findings from the empirical data and the literature review. As the empirical data, this research utilized semi-structured interviews in the case context of the Finnish plastic value chain. The process and choices made related to the interviews are further elaborated later in section 3.3. After the data collection, an analysis of the interviews was carried out, utilizing a more inductive focus of reasoning with elements of the Gioia methodology (Gioia et al., 2013). The analysis process is also further elaborated later in section 3.3. Finally, the results of the interview analysis and the literature review were considered together with an abductive approach to draw insight regarding the research questions.

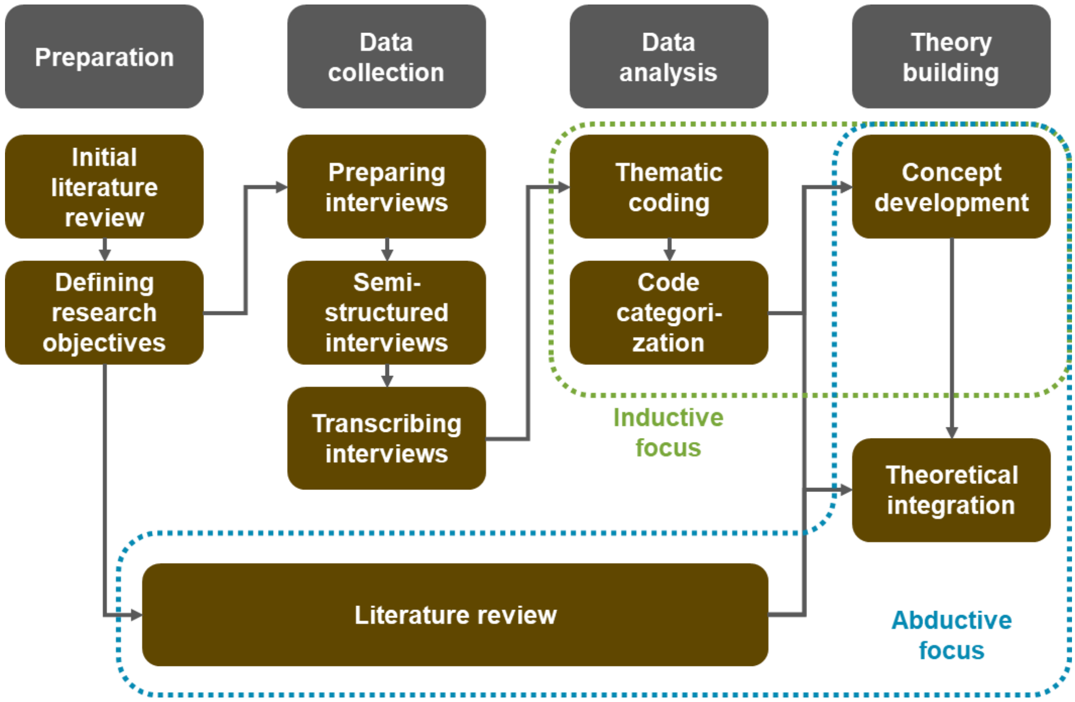


Figure 6: Illustration of the research process

3.2 Conceptual approach – modelling the plastic economy as an open system

In the previous section, the general design of the research was elaborated, and the conducted research process was discussed. In addition, the study utilized a framework to understand the operation of the plastic economy on a system level. This framework was constructed based on the initial literature review, and it influenced the formulation of the research questions. The framework was also used to structure the analysis and results in combining the literature review and the empirical findings into theoretical insights. The framework, which is an open system model of the plastic economy, is presented next in greater detail.

As discussed in 2.3, thinking related to the circular economy emphasizes a systemic perspective, in which it is seen that, if only parts of a system are considered, it is likely that improvement efforts towards circular economy and sustainability will lead to sub-optimal outcomes (Ellen MacArthur Foundation, 2013). To consider a systemic perspective, this study employs a system model in examining the economic system of plastics and its environmental effects, and to study the effects of biocomposites to the system. The conceptual model describes the plastic economy as an open system. An illustration of the model is given below in Figure 7.

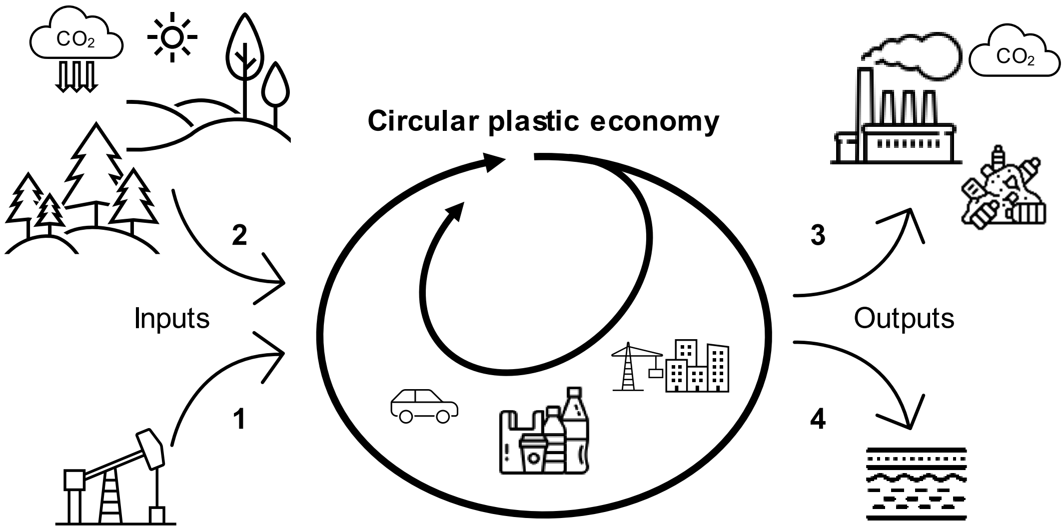


Figure 7: Open system model of the plastic economy[1]

The open system model of the plastic economy is essentially an input-output model that describes on a systemic scale how the plastic economy transforms different input to eventual outputs. Essentially, the plastic economy takes different inputs from its environment, uses the inputs inside the plastic economy in various ways, and finally creates different outputs back into its environment. Since the plastic economy requires inputs to operate, and creates outputs that affect the environment, such as pollution, the plastic economy may be seen as an open system rather than a closed system.

Although the model may consider many different inputs and outputs to the system, a crucial element in the plastic economy system is carbon. It has an essential role in the production of plastics as a critical required element, but also in the harm that greenhouse gases, typically including carbon, have for the external environment. Therefore, the plastic economy system is especially examined by considering the circulation of carbon in relation to the plastic system. Next, the elements described by the open system model are explained in greater detail, especially examining the circulation of carbon. Furthermore, it is elaborated how the conceptual model is utilized in the study as an analytical framework.

[1] This illustration has been designed using images from Flaticon.com.

Firstly, the open system model considers the inputs needed in the plastic economy, which are illustrated in the left-hand side of Figure 7. As discussed in chapter 2.1, the essential raw material for plastics are hydrocarbons, which can, in principle, be sourced from any source of hydrogen and carbon (Andrady & Neal, 2009). Currently, the main source are fossil resources (Palm & Svensson Myrin, 2018), which are described as the primary input in the model (Figure 7, flow 1). However, bio-based raw materials may be also used as a source of hydrocarbons (Di Bartolo et al., 2021). Bio-based inputs are described as flow 2 in Figure 7. Generally, the fossil input flow is considered environmentally negative, as the use of fossil resources creates GHG emissions to the atmosphere. On the contrary, bio-based inputs may provide a renewable source that has the capacity to replace fossil inputs (Acquavia et al., 2021). Furthermore, the bio-based inputs originate from plants, which have through photosynthesis the ability to capture carbon dioxide from the atmosphere (Suh & Bardow, 2022). Therefore, by utilizing the bio-based inputs, carbon may be captured away from the atmosphere and into the system (Stegmann et al., 2022). A desirable direction in terms of system inputs is to then aim to maximize the bio-based input (flow 2) and minimize the fossil-based inputs (flow 1).

Secondly, the model describes the operation of the plastic economy itself (illustrated in the middle of Figure 7). The inputs are used within the plastic economy in the production of plastics. Plastic materials are then used in various applications, and after use there may be several alternative pathways for the material, as discussed in chapter 2.4. From the systemic perspective, the negative implications of plastic use may be limited by keeping the material in circulation within the plastic economy by recycling or other circular practices (Ellen MacArthur Foundation, 2017). This way, the service life of the material may be extended, which increases the value gained from the use of the material. Increasing the circulation of plastic also limits the need for new inputs to the system, as well as decreases or at least postpones harmful outputs. Therefore, it is considered desirable in the modelling that the circulation is increased, and the service life of plastic materials are extended in the plastic economy.

Lastly, the model describes the outputs of the plastic economy system, which are illustrated on the right-hand side of Figure 7. Although plastic materials may circulate within the plastic economy, at some point they will also exit the system. Flow 3 in the model describes the harmful alternatives of after-use disposal, namely the incineration of plastic which creates carbon dioxide emissions, or the creation of plastic waste in the environment through landfilling or littering. These output flows are clearly negative for the environment due to effects on climate change or effects to natural ecosystems. However, as was identified in 2.4.4, there may also be alternative disposal routes that overcome the negative effects to the environment from plastic disposal. Flow 4 in the model describes these alternative routes for the disposal of plastic wastes, which either capture carbon embedded in plastics to long-term storages, or return carbon safely to the biosphere through, e.g., effective biodegradation. From the systemic perspective, flow 3 should then be relatively minimized and flow 4 relatively maximized.

Based on the thinking above, Table 10 below summarizes the changes that should happen in the plastic economy to transition to a sustainable plastic economy as modelled by the open system model. As has been established in this thesis, the current state of the plastic economy unsustainable as the economic system heavily relies on fossil inputs, the circulation of plastic within the economy is rather limited, and the main routes for disposal create either emissions through incineration or plastic waste to the environment. Completely on the contrary, however, the plastic economy could also be envisioned to act as an emission capturing system, as discussed in 2.4.5. This would require the plastic economy to completely reverse these flows to a way that captures atmospheric emissions using bio-based inputs, circulating materials within the economy as long as possible, and eventually storing them to a long-term depository. Any gradual changes in these directions could be considered positive for the environment, compared to the current unsustainable state.

Table 10: Desired change directions of carbon dynamics in the plastic economy open system model

<table>
<tr><th>Stage in the model</th><th>Type of flow</th><th colspan="2">Desired directions of change</th></tr>
<tr><td rowspan="2">Input</td><td>1. Fossil-based</td><td rowspan="2">Decrease total input.</td><td>Decrease relatively.</td></tr>
<tr><td>2. Bio-based</td><td>Increase relatively.</td></tr>
<tr><td>Plastic economy</td><td>Circularity of economy</td><td colspan="2">Increase circularity and extend service life of materials and products. Thereby, decrease both inputs and outputs, and keep carbon in use within the economy.</td></tr>
<tr><td rowspan="2">Output</td><td>3. Emission or waste</td><td rowspan="2">Decrease total output.</td><td>Decrease relatively.</td></tr>
<tr><td>4. Carbon storage</td><td>Increase relatively.</td></tr>
</table>

The model described in this section is utilized in this study for multiple purposes. As a background premise, the study recognizes bio-based plastics as a possibility to increase the relative bio-based input flow and reduce the fossil-based flow. However, as identified in 0, bio-based plastics are also seen problematic, but biocomposite materials can be seen as an alternative solution to increase the bio-based input. However, the main research gap can be described such that the previous literature is limited in understanding how biocomposite materials impact the plastic economy's ability to transition towards the other positive directions described in the model, namely extending service life of plastic materials through circular strategies and increasing outputs to long-term carbon depositories. Therefore, the main research questions (presented in 1.2) are formulated with the logic of the open system model in mind, namely by validating how biocomposites could support moving in directions summarized in Table 10 above. The open system model is also utilized in structuring the analysis of the empirical data, as is explained later in 3.3. Finally, the open system model structures the conclusions to the research questions, by modelling how biocomposite materials could allow the plastic economy to transition towards environmental sustainability.

3.3 Data collection and analysis

As empirical data in the case study, this thesis utilized interviews with actors in the plastic value chain within the case context. Based on the initial literature review, it was evident that the plastic value chain can be seen as a rather complex industrial system. It seemed clear that the specific materials used in the industry, such as biocomposites evaluated in this study, have different kinds of impacts to different kinds of actors that operate in different stages of the value chain and with their own operating logics. Acknowledging this diversity of actors and the complexity of the system was a fundamental principle in choosing what kind of actors the study targeted to interview.

The interview sample was constructed so that the interviews would cover all relevant stakeholders in the plastic value chain. The relevant stakeholders were identified based on an initial stakeholder mapping that was based on the initial literature review, and it was further iterated based on the first interviews. After identifying the relevant stakeholders, relevant persons were identified from the organizations, and they were contacted to propose an interview. The interviews also guided to contact further interviewees. The interviews were continued until saturation was achieved in the information that each new interview brought. In total, 19 interviews were eventually conducted, which are listed in Table 11 below. All interviews were conducted during May and June in 2023. To ensure that the data collection was conducted reliably, each interview was recorded. The permission to record and the consent to data handling policies were asked from the informants at the beginning of each interview.

Table 11: List of conducted interviews

Company role in value chain	**Acronym**	**Informant role**	**Duration (min)**
Biocomposite production	A	Director	82
	B	Technology development manager	86
	C	Head of R&D	88
Plastic product manufacturing	D	Chief Marketing Officer	53
Polymer production	E	Programme Manager	57
Refining	F	R&D Manager	83
Recycling	G	R&D Project Manager	66
	H	Account Manager	56
	I	Account Manager	56
	J	Leading Expert	62
	K	Chief Executive Officer	75
	L	Chief Technology Officer	85
Municipal waste management	M	Project Manager	98
Industry association	N	Chief Advisor	84
	O	Expert	90
University or research institute	P	Research Scientist	63
	Q	Doctoral Researcher	63
	R	Research Scientist	92
	S	Research Scientist	75

The interviews were conducted with a semi-structured interview approach. For case studies, semi-structured interviews are generally recommended as the principal method for gathering data Gioia et al. (2013). The approach is considered appropriate especially when the study aims to understand how the informants understand the social world under study (Qu & Dumay, 2011). In addition, the semi-structured interview approach was chosen because of the explorative nature of the study and the complexity of the studied industry system, for which a semi-structured rather than a structured approach provides more flexibility and ability for the interviewer to react to the information given by the informant.

The interviews were organized around an interview guide that structured the conversation. The used interview guide can be seen in Appendix A. The guide incorporated guiding questions that were supplemented with additional probing questions to encourage more in-depth responses (Qu & Dumay, 2011). The design of the interview guide followed the principles outlined by Gioia et al. (2013), such that the questions focused on answering the research questions and as support optional clarifying questions were posed. In addition, efforts were made to pose the questions in an open-ended and non-leading manner. During the interview, some initial findings from the initial literature review were shown to the informant, the purpose of which was to orient the informant to the context and focal areas of the research. As part of the material shown, a mapping of the plastic value chain and different end-of-life strategies for plastics was shown to structure the conversation. This mapping was constructed based on the initial literature review to provide an initial framework as a model of the plastic economy system. The mapping can be seen in Appendix B.

After the interviews, each interview was transcribed based on the recordings. The process of analyzing the interviews and eventually combining the empirical findings with the findings from the literature review was inspired by Gioia et al. (2013) and Eisenhardt (1989). The analysis of the interview data began with an inductive focus by open coding of the data and categorizing data to higher order constructs. To support analyzing the interview material, the study utilized the Atlas.ti software which is a tool for analyzing qualitative data. The interview transcripts were first thoroughly read through, and relevant quotations were highlighted. The quotations were marked with a code summarizing the main content of the quotation, using mostly the terminology of the informant as suggested by Gioia et al. (2013). At this point, the codes were still very detailed and on a low level of aggregation.

After highlighting and describing the quotations from all interviews with codes, the set of codes were exported to a Miro board, which is a visual whiteboard tool. In Miro, a visual illustration of the open system model presented in 3.2 was utilized to structure the categorization and analysis of the codes. Using the visual tool, the codes were grouped together based on logical connectedness. In addition, the code groups were connected to some stage in the open system model; either related to the inputs to the plastic economy system, related to the operation within the plastic economy, or related to the outputs of the system. The code groups could also be related to several of these stages or to the whole system. These groups then formed the 1st order concepts. With grouping codes to 1st order concepts, the main high-level findings started to emerge. There were still a substantial amount of the 1st order concepts, so they were further aggregated to form 2nd order concepts. The 2nd order concepts then essentially formed the main findings from the interviews, which are reported in chapter 4.

Up until forming the 2nd order concepts as the main findings of the interviews, the focus of the data analysis was inductive. However, after the interview analysis the focus of the study turned to the abductive approach, such that the findings from the interviews were combined with the findings from the literature review to establish theoretical integration. From this in-tandem analysis, the study concluded the main results of the study related to the research questions. These main results are reported in chapter 5.

3.4 Assessment of the research design

According to Yin (2009), the quality of any empirical social research is commonly evaluated against four main criteria: construct validity, internal validity, external validity, and reliability. The quality of this research study is next evaluated against these criteria.

Construct validity relates to the degree in which the research is studying the phenomenon it claims to study (Gibbert et al., 2008). This study addresses construct validity by using multiple sources of evidence to interpret the findings, as recommended by Yin (2009). As multiple sources the sampling for the interviews focused on targeting several types of value chain actors within the case, as well as also considering findings from literature in the abductive reasoning. In addition, some publicly available information regarding the industry and the value chain actors was used in the beginning to understand the plastic economy context. Furthermore, the data analysis process establishes a clear chain of evidence in how the interview data was interpreted to interview findings, which also addresses construct validity (Yin, 2009). A threat to construct validity may still be identified in the fact that this study rather investigated empirically the perceptions of the plastic value chain actors towards the sustainability of biocomposite materials, rather than aiming to somehow quantify the impacts on sustainability. However, at this point the scientific understanding about the practical implications of these materials is limited, so the explorative approach taken in this study can be seen as a prerequisite for further quantitative studies in the area. Moreover, the investigation focused on perceptions of actors may reveal the inner logics and complexities of the industry system better, which could have been difficult to identify without the approach taken.

Internal validity is related to the causality between the focal variables and the logical reasoning behind the results (Gibbert et al., 2008). As pointed out by Yin (2009), internal validity is not generally a concern in descriptive or explorative case studies since the logic of causality is mostly missing, which is not the case in explanatory case studies. Therefore, it is not an applicable quality measure for this study since this study does not aim to confidently establish causal relationships between events, but rather aims to identify events and conditions, and explore possible relationships between them. These aims also underline that this study may act as groundwork for further explanatory studies that aim to test the theories built in this study.

External validity means how well can the results of the study be generalized beyond the specific case studied in the research (Gibbert et al., 2008). This study supports external validity by having rather broad empirical evidence from 19 informants representing widely different types of actors in the plastic value chain. This evidence can be estimated to give externally valid interpretations that measure the whole plastic value chain. Although the research design utilized a single case study, which may be seen as a threat to external validity, the chosen case is evaluated as a representative case, where the findings to the research questions could be explored credibly. It is likely that the findings can be well generalized at least to other economies in Europe, but naturally there may be country-specific differences that affect the results if the same type of investigation were conducted in another country.

Finally, *reliability* refers to the quality of the research process such that the same results would be achieved if the study was repeated (Yin, 2009). To address reliability, in the analysis process efforts were made to document each step carefully to increase transparency of the interpretations made. In addition, a case study database was constructed such that all information and documentation of analysis procedures were stored for later use and for possible evaluation and replication. It is likely for this study that the same results would be achieved if another investigator would conduct the research process.

However, some threats to reliability may have originated from different biases. According to Saunders et al. (2009), interviewer and interviewee bias may have effects on reliability of results, especially when the empirical findings rely on semi-structured interviews. Interviewer bias relates to the interviewer's behavior, such as tone or non-verbal behavior, which may affect the responses of the interviewees (Saunders et al., 2009). Although the effects of interviewer bias cannot be ruled out, the interviewer made efforts to mitigate such biases and remain neutral to whatever the informants were saying. Interviewee bias, on the other hand, refers to interviewees withholding information because of sensitivity of information or because some information could present the informant or the organization negatively (Saunders et al., 2009). This bias cannot either be ruled out, but it is difficult to think of reasons why the informants would not have shared some information or would not have told the truth. Also, many respondents openly shared information that could possibly be seen negative to their public image, which also demonstrated that the data collection was designed so that informants were comfortable sharing information.

There may also be other biases. For instance, Robson & McCartan (2016) identify participant bias as a possible threat to reliability, which means that informants may tend to act and respond in a way as they perceive the interviewer to want them to respond. Again, this bias cannot be ruled out, but the questions posed to the informants were purposefully presented in an open-ended and non-leading manner, which likely mitigated this bias. Finally, there may also be researcher bias in the interpretation of interview data, which refers to the tendency of an observer to see what they want to see, because of their own biases and beliefs (Robson & McCartan, 2016). This bias may be a threat in any qualitative research, as the interpretation of the findings are ultimately dependent on the subjective evaluation of the researcher. In this study, the bias was mitigated by continuously discussing the interpretation of the results with the supervisors of the thesis.

4 Findings

In this chapter, the findings of the empirical part of the study are presented. From the interviews, nine main findings were discovered. The findings are grouped into three categories based on the lifecycle stage that the findings relate to, and one category that concerns systemic effects. First, the chapter discusses findings that are related to material choices for products, the applications of biocomposites, and the production of biocomposites. Secondly, the findings related to the recycling of biocomposites are explored. Thirdly, the chapter reports findings that relate to the end-of-life stages of biocomposites. Finally, a finding related to the systemic perspective is elaborated. In the end of the chapter, a summary of all the findings is offered.

4.1 Material choice and production of biocomposites

First, the thesis introduces findings from the interviews that relate to choosing materials for products and to production processes. In this category, three findings were identified, which are presented next.

Finding 1: The adoption of biocomposites is mostly driven by the valorization of side-streams and improving carbon footprint of the material by increasing bio-based content.

It was highlighted that a central driver for developing and commercializing biocomposite materials from the producers' perspective has been to valorize side-streams that have previously been wasted. Informant R confirmed previous understanding that *"[typically, biocomposites] can utilize side-streams from different [...] forestry wastes, and agricultural wastes"*. An informant from a forestry company, which produces biocomposites, highlighted this valorization as a central driver:

> *"We use our internal production waste [...] Our driver [for producing biocomposites] is aiming to utilize the waste generated by the side-streams of pulp, paper, and sawmill production. [...] The driver is to minimize those [wastes] [...] and to decrease [waste streams] that nowadays go to incineration."*
> *– Informant B*

From the perspective of plastic converters or brands, on the other hand, the main driver seems to be their sustainability values, for which the maximization of bio-based content of products and minimizing the carbon footprint of the used materials are central objectives. According to a producer, "*the benefit [of biocomposites] is [...] the bio-based content. [...] We go up to 50% wood fibers, so up to 50% of the contents [of the material], and then you can even put in the bio-based polymer there, and nearly 100% bio-based [material as a result]*" (Informant A). An informant from a plastic product manufacturer, that has used biocomposites in their products, stressed the importance of increasing bio-based content:

> *"It is very important, that [...] when we replace a traditional fossil-based plastic with, let's say, a bioplastic or recycled plastic, the carbon footprint [of the material] decreases 60-100%. So, it has a significant effect, and because of that it guides our work a lot that how we could change our materials to recycled plastics or bio-based plastics as much and as quickly as possible. [...] We specifically wanted to replace this fossil-based plastic with a plastic that is more environmentally friendly and has less carbon footprint. That was the idea [in launching products based on biocomposites]." – Informant D*

Finding 2: Biocomposite materials are limited in where they can be applied but are more likely beneficial in longer life non-packaging applications.

In general, it was pointed out in the interviews that the properties of biocomposites are often challenging, which, therefore, limits the possible products where such materials can be applied. According to informant P, "*usually the properties of biocomposites are less than the plain polymers*". One mentioned issue is that biocomposites may have good strength and stiffness, but poor impact strength. Informant P claimed regarding a commercial biocomposite that "*the stiffness is very high, but it's very brittle. Then it's very difficult to find an application for this very brittle material*". A biocomposite producer described that the impact strength is a rather central issue:

> *"If you just look at the material, you could say, yeah, it's super strong, and sort of stiff. But in a lot of applications, that's not really relevant. So I think what I see in research sometimes that's a bit, you know, misleading, is looking at these type of properties like strength and stiffness, and comparing those properties to plastics, and then it's like, oh the biocomposites are great. Yeah, okay, those properties are great, but how important are those properties versus impact strength, which is not so great. And in reality, in real life, in consumer products,*

for example, which is the biggest segment that we currently operate, impact strength is significantly more important than stiffness and strength." – Informant A

It was also criticized that natural fiber fillers can rarely reinforce the material in a way that biocomposites could compete against plastics that are otherwise reinforced with glass, carbon, or aramid fibers. Informant O noted that "*natural fibers, some of them are reinforcing and some not, most of them are not. They are more for just [...] making the material cheaper. Talc and others have been used in a similar way, to make cheaper and less demanding materials, no more than that. Properties come along if they do, and hopefully those are better properties than worse.*"

For these reasons, it was often mentioned that biocomposite materials cannot be applied everywhere, at least if the properties do not match the functionality required in the application. A biocomposite producer stressed that "*the application comes first, so the functionality [of the material] is crucial, and [...] we would not be pushing [the biocomposite] to every application, that does not make sense, and this concerns all biocomposites [on the market]*" (Informant C). However, it was also pointed out that there may be underlying flexibility in the requirements for many applications:

"The good thing is that most of the materials used or most of the applications have properties that could be overestimated. Sometimes because you have been using a particular material for a particular application you set the properties of that application with a particular standard. However, you can utilize low-quality materials that can achieve the same [...] application. Therefore then you could optimize the use of materials or use of [biocomposites] for achieving the properties that is required for that application and not the property that are set because they have been always used with the same material. [...] I remember cases in my previous work where we were trying to substitute some[product] with some biocompounds, and when we ask the producer why they are using those specification of properties, like [...] brightness or hardness and so, they would say that is the property of the material we have always used, that typically have been either polypropylene or could have been ABS or those materials. But do you really need those properties, and said, we don't know, we have always been doing the same. That is the opportunities for the [biocomposites] there." – Informant F

Many respondents noted that the most likely application areas are in applications that are used for a longer time and are not packaging applications.

Some applications that were mentioned are various consumer and household products, construction applications, furniture products, and automotive applications. Many respondents criticized the use of biocomposites in packaging applications due to their effects on the recyclability of packaging plastics (these findings are covered more thoroughly later in 4.2). In addition, it seems that biocomposites are more likely adopted in more premium segments where the higher price of the material is accepted, and some of its properties, such as a natural look, may bring additional value. An informant from a biocomposite producer characterized that *"currently, the biocomposite market is strongly focused on premium or luxury brands [...], because there is a slight premium in the price since volumes are smaller, and they cannot yet compete against fossil-based materials with the price"* (Informant B). A plastic product manufacturer highlighted that biocomposite could also be a positively distinctive material:

> *"We believed that [using a biocomposite] could result in commercially nice looking and distinctive products. [...] Normally, if you use, for instance, sugarcane, bio-based plastic, nobody distinguishes that it is based on sugarcane. It is just written in the package that this is bio-based plastic, but [from the biocomposite] you can see that it is something different."*
> *– Informant D*

Finding 3: The production and supply chains of biocomposites have drawbacks compared to conventional plastics, which hinder the adoption of biocomposites.

In general, it is considered that biocomposites can be produced using the same processing equipment and technologies as other plastics, and this view was widely confirmed by the respondents. However, it was pointed out that changes must be made in the processes although the same equipment is used. Eventually, the costs of producing biocomposites are rather high, which makes it difficult for them to compete against fossil-based plastics.

According to informant R, producers typically "*have to modify the compounding process and include various additives to make the material applicable for converting*". Many informants pointed out that compatibility between the fibers and the polymer matrix is crucial for the resulting material to have good properties. To achieve compatibility, additives may need to be added or the natural fibers may need to be extensively processed. A concern was raised that "*sometimes these compatibility methods, they are not very green and sometimes they are also very costly*" (Informant P). However, biocomposite producers were not too worried about the sustainability or costs of achieving compatibility:

> *"It's not really a challenge. There's quite good commercial solutions for that, that don't need to be used in high volume and they're also not really that... They're not an issue with respect to sustainability, either." – Informant A*

In addition, adding natural fiber fillers into the polymer in the compounding process may make biocomposite production more energy consuming than other plastics. As informant P put it, "*[the compounding] is one more energy-consuming process. Because we need to compound them, blend them, [...] therefore we need to apply more energy*".

Biocomposites may also bring other challenges to the processes. A biocomposite producer stated that "*it would be nice if you could use almost 100% of natural fiber in the material, but then there will be certain limitations regarding processability [compared to fossil-based materials] that you cannot get it flowing as properly and so on. [...] These may be technically solved in the process, but they create additional costs*" (Informant B). The thermal sensitivity of the natural fibers was mentioned as one limiting factor in processing biocomposite materials, which must be controlled more precisely. A plastic product manufacturer described that the thermal sensitivity has been an issue in the processes:

> *"We have had issues with our molds, [the biocomposite material] has burned our molds. We have had to recoat our molds and manipulate them. [...] Replacing regular plastic has not been easy, but the process has required work for it to function. [...] The wood slightly burns in the production processes, [...] when you use injection molding, the material gets very hot. Then [the wood fiber] is slightly burning in the mold, so [the biocomposite molding] is very hard on the mold." – Informant D*

However, it was also pointed out that any new plastics will either way need some modifications and engineering work in the production processes. Informant A said about biocomposites that "*it's just like any other sort of plastic material. So, there's plastic materials that you can't just swap in and out of the same mold either. Like you can't use ABS in a PP mold with great success. [...] You have to consider what the mold was made for, and then make adjustments*". Therefore, learning to process biocomposites is essential for them to be adopted: "*You have to know what you are doing, like with everything else, [...] but in my opinion [processing biocomposites]* *is not really a much greater challenge than any other new material."* (Informant O).

Nevertheless, biocomposites were seen to increase complexity of the supply chain, as the sourcing of natural fibers is additional to sourcing only polymers. The uncertainty of natural fiber supplies may become an issue: "*If we reach a large scale, how can the industry guarantee a certain supply, because for instance hemp or something else that is grown, it depends on the year what the yield is*" (Informant O). Informant F, on the other hand, stressed the importance of scalability and logistic issues of materials based on wastes:

> *"I have seen hundreds of projects in Europe for new applications of [biocomposites], using very weird material, like waste from oranges or waste from this and that. And then just, okay, when if you want to go to the high-volume industrialization or high scale, then you starting to face that okay, how you can put everything in a center to produce high volumes where you can actually target big brand-owners. If you go to sit with a big brand owner, they're going to say okay, I like this material, this material works perfectly, it has all the requirements we have, definitely, we need five tons per day, can you provide that. And then they say okay, definitely it's technically possible, where do I get the material for that. And I have seen many projects where that is the key point, where they say okay, technically everything is possible, you will always find an application for a particular material but then you will be limited by the logistic scale" – Informant F*

4.2 Biocomposites in plastic recycling

Secondly, the interviews revealed findings regarding biocomposites in plastic recycling. Connected to this topic, three findings were identified, which are presented next.

Finding 4: The current recycling system of plastics discourages the adoption of biocomposites.

Many respondents in the interviews stressed that the current recycling system is rather limited. A central limitation is that the system strongly differentiates plastic packaging wastes and non-packaging plastic wastes, such as plastic consumer products. This problem comes mainly from regulation and who the regulation mandates to pay for recycling. Informant R described that "*in Finland, plastic recycling officially concerns only packaging wastes, if we are talking about post-consumer wastes, it concerns only packages. […] In principle, [a consumer] should not put any other plastics [than packaging] into the recycling*". However, "*for plastic products, there is no [recycling] system yet*." (Informant E). Informant O highlighted this contradiction:

> *In principle, all the [plastic] material could go to the same recycling system, mut in Finland it is the packagers who pay for the system. [Plastic] product manufacturers are not in the product responsibility system […]. [Many plastic products] are exactly the kind of material that is wanted for mechanical recycling. But, when the manufacturer [of the plastic product] is not in the product responsibility system, they don't pay for [the recycling], and their product also doesn't belong there [to the recycling system]. – Informant O*

A limitation is also that the recycling rate of plastic waste in the current situation is only around 30%. The low rate not only originates from the limitations of the quality of the mixed plastic waste and the recycling itself, but also from the collection system:

> *"[In Finland] the collection rate is about 41%, and conversely 58% of packages go somewhere else, meaning to mixed waste collection, energy waste collection, or wherever, but does not go to the collection system [for recycling]. And when the EU's goal for plastic packaging in 2025 is to recycle 50%, then it is hard to recycle 50% if you only collect 40%. So, the consumer behavior is the most challenging part of it, [the collection rate] should be at around 80% for the recycling rate to even possibly be 50% of total." – Informant K*

The current recycling system is also rather limited to a handful of main commodity plastics, such as PE, PP, and PET. For these, the volumes in the waste streams are sufficiently large for them to be sorted from the mixed waste streams and recycled. Behind many of the limitations is also that recycling mostly relies on mechanical recycling, and chemical recycling is not yet available on an industrial scale.

In general, the recycling system seems to prefer plain or pure monomaterials that have a simpler structure rather than multimaterials where many materials are attached or mixed together. Informant F claimed generally that "*the rule of thumb is that the purer the material, the easier it's to recycle*". Informant O gave an example:

> *"If you think about polyethylene, as pure polyethylene it may be recycled very well. There is in a way no problem. It is simply grinded and then just thrown in. But always when you put something else in it […] So the less you mix anything into a material, the easier recycling will be." – Informant O*

A challenge in the recycling system has been for instance various multilayer packages, where some of the plastic is replaced with, for instance, paper or cardboard. Informant E gave an example: "*I mentioned the liquid packages. In those you have a plastic layer and a cardboard layer, and the problem is that when they are sort of glued into each other, you cannot really separate them.*" The issue may also be the use of many plastics, as "*many packages have many layers of different plastics just because the properties of one plastic is not enough*" (Informant O). These structures are problematic because "*in general, the multilayer structures are very tricky to be recycled"* (Informant L).

Because of the limitations of the current recycling system, most of the informants criticized biocomposite materials for being very hard to recycle in the current system. The addition of fibers was criticized for causing a "*fundamental problem […] that a good recyclable plastic is made unrecyclable by blending it"* (Informant K). Many respondents saw the recycling of composites in general as very challenging for the current system.

A central issue pinpointed in the interviews was that the biocomposite approach increases the complexity of identifying the material in waste streams for it to be recycled:

> *"We get to the challenge that we may have ten different polymers and then a quite large selection of fibers, so how can you identify them, how do you recycle them, can they be recycled together or do they need to be separated […] The logistic problem increases manifold both in recycling and identification, the identification gets more difficult because there are different fibers and different plastics." – Informant R*

Moreover, it was highlighted that tracking the quality of the material may be increasingly difficult in recycling blended materials like biocomposites. The same issues are present currently with polypropylene where fillers are added:

"We already now have a challenge with PP, polypropylene, when talc or chalk is put in it, so what when you have one package with 5% and one with 30% [of filler]. Yes, we can recycle it quite ok, but we are going to have a PP-stream with an undefined amount of talc, and for everything, the quality grade, when you start to make packages of it, there should be the amount of talc defined, so how can we know it? How can we say it in any way?" – Informant K

Because of the challenges of recycling, biocomposites are very likely to be rejected from the waste streams and incinerated for energy purposes. Among the respondents, this was generally seen as a negative aspect which discourages the adoption of biocomposites. On the other hand, biocomposites were not seen to negatively impact the current mechanical recycling streams since "*[biocomposites] will just get filtered out and then burned, so it's not causing any issues to the [recycled material] itself [or its quality]. So, it's not negatively impacting the system in a way*" (Informant A).

In general, it was reflected in the interviews that the industry is currently mostly focusing on recycling and sees it as the most important thing. For instance, a plastic product manufacturer said that "*recycling is important in my opinion, whether it is a recycled material, a conventional plastic, or a bioplastic, then to be able to recycle it and use the material again is the most important thing when we look at the future*" (Informant D). Informant P considered it even more important than bio-based materials by saying that "*nowadays people talking about developing new biopolymers, developing some biocomposites, but in my mind [...] [if we work on] the circularity of these petroleum-based polymers, we may get more environmental impact than developing new bio-based polymers or new biocomposites. I think we should focus more on the traditional polymers, but on making them circular. I think it is more efficient*" (Informant P). Therefore, it was natural to see that many of the respondents were critical towards biocomposite materials, as they may be challenging to recycle in the current setting.

Finding 5: The current plastic recycling infrastructure would require changes to accommodate biocomposite recycling.

Although the interviews revealed criticism towards biocomposites for preventing the mechanical recycling of the material, it was uncovered that this prevention of recycling does not originate from properties of the biocomposite materials, but rather from the configurations and logics of the recycling system itself. In fact, it was highlighted that, technically, biocomposite materials may be mechanically recycled similarly as other plastics, as they are essentially thermoplastic materials that may be melted and reused again. One of the biocomposite producers has showcased that the performance of the biocomposite material has been very good in recycling:

> *"I would say that the fibers are the durable part of this. [...] So we've done a few studies where we look at the recycling, and we have shown that in general we can perform even better than some plastics in terms of recycling performance over time. And we've also done a study where we do heat aging, so simulating time in use. In between cycles, we did specifically, we did an experiment for the use case of clothes hangers, which are primarily today made from polystyrene. And they have quite good closed loops for the hangers, so they're often recycled and then repurposed, made into new hangers again, this polystyrene. And we did a direct comparison study with polystyrene, where we did the recycling, heat aging, and then recycling again and again and again. And overall, for the majority of the properties we were [with the biocomposite] performing more stable over time, than polystyrene." – Informant A*

However, in the recycling of biocomposites there may be substantial coloring issues due to the thermal sensitivity of the fibers, resulting to a darkening of the material when heated as part of recycling. However, this may not pose a significant issue, because "*the color can also be addressed by simply adding some virgin material, as everyone does with all recycled plastics. No one's using a 100% recycled plastic in a product*" (Informant A).

As technically biocomposite materials can be recycled with similar limitations as other plastics, the configurations of the recycling system itself would need to change somehow for biocomposite materials to be recycled. One approach that was brought up by many respondents was that the recycling system should move more towards small loop structures and practices (see 2.4.3). Many respondents considered that the recycling of biocomposites could operate better if it was implemented through small loops or closed loop recycling, or that such an approach is even required. By implementing small loops, the waste stream would be less contaminated, and it may be better known what is in the material, which is especially crucial for biocomposites that are seen complex due to a diverse set of both polymers and fibers that may be used in them. Informant R highlighted that these could be implemented "*possibly [through] take-back schemes, so the manufacturer takes back their [product] and recycles in a controlled way in their own systems, or then new actors who start to collect these biocomposites separately for separate recycling [...] These take-back schemes can be* *seen already for instance in the cosmetics market, that you can return the cups and jars, and then they go to a controlled recycling*" (Informant R).

Furthermore, many of the respondents perceived the constraint of recycling solely focusing on packaging waste as a limitation that should be expanded to include also other types of plastic. As identified previously in Finding 2, biocomposites are especially a potential material in longer life non-packaging applications, such as consumer products, rather than packaging applications. Therefore, the development of the recycling infrastructure in these non-packaging segments of plastic waste is especially important for biocomposites. A plastic product manufacturer recognized development in this area as an important next step:

> *"This plastic recycling is still in its infancy, now we have been learning to recycle these packages. It is of course a large share, they are single use plastics and they create a huge amount of waste. People buy them constantly, there is a lot of it, and it is really good [that it is recycled] but the next step must absolutely be the recycling of all other plastic." – Informant D*

As currently the recycling (in the Finnish context) is mostly funded by the product responsibility scheme of packagers or packaging manufacturers, "*the cost model must change when all [plastic] is circulating*" (Informant N). Expanding the sectors of plastic waste sources was noted to require a large transition, as "*the whole infrastructure for the recycling of these other than packaging plastics [...] must be created at least in the scale of Finland. In Europe, there are already some systems in place, but in Finland practically not*" (Informant R).

Finally, many of the informants simply pointed out that, for biocomposites to ever be recycled, they should essentially be either collected as a separate stream or sorted to a separate stream from a mixed plastic waste stream. The latter was considered technically feasible in the current automatic sorting technologies:

> *"Both biopolymers and our biocomposites can be very efficiently sorted from the streams, so that they do not end up in the polyethylene or polypropylene fractions [...] The NIR [identification signal] is so different [from others] that they currently go to reject, but if wanted, it could be well separated as its own stream" – Informant C*

Some informants even considered that biocomposite wastes should be managed totally separated from plastics:

"In my opinion it should be kept separated, plastic and biocomposite should be completely separate, a bit like metals, glass, and so on. So these should be a stream of their own, these should not be messed up with plastics in any way."
– Informant H

As a possible tool in the separated collection, some informants highlighted the recycling symbols or labeling in plastic products and packages. According to informant B, "*the biggest bottleneck still in recycling is that the recycling label [for biocomposites] is 7, so there must be a change that it would be more clearly defined as its own*". Whereas the main commodity plastics have their own number in the EU's recycling labeling system (such as 1 for PET and 5 for PP), the category 7 is a mixed category of 'other' than the main commodity plastics which have their own numbers. Creating a distinct label could then allow to facilitate the separate collection of biocomposites:

"Maybe the easiest would be to implement [...] a distinct recycling symbol for biocomposites, which could enable to take them to somewhere where the labeling guides. Whether it is returned to the stores where they are bought from, or whether the collection system expands so that it accepts also other than packaging plastics, [the clear labeling] could allow consumers to recognize that, aha, this is a biocomposite, this must be returned to a specific place, to a specific bin, or a specific store, or a specific something, then it would be easier for [the material] to end up in controlled recycled, rather than to mixed waste or incineration." – Informant R

Finding 6: The economics of recycling dictate how the recycling system may accommodate biocomposites.

It was often reflected in the interviews that, in the end, recycling must be a profitable business for recycling companies. An informant from a recycling company stressed that profitability should be the starting point rather than mandating recycling by regulatory forces:

"I want to distinguish two things: recycling as an activity and recycling as a business. The activity of recycling can be run with government support or something like that, but it is not sensible in the long run, so recycling should, by itself, be profitable as a business, in such a way that we would get such good material from the recycled material that it can be sold and it is interest-

ing to industry, which is when it covers its own costs. With regulation you can easily just create market distortions here." – Informant K

Many respondents highlighted that the market forces and incentives related to both plastic wastes and recycled materials have a crucial role in how waste is collected and recycled. According to informant L, the collection of plastic waste is still rather limited because "*the market must be first created for the collected plastic waste, the market does not function properly yet*". Informant F pointed out the importance of incentives in improving the collection of plastic waste, such that with a better market mechanism "*you are [...] activating, enabling the profitability of collection, so you indirectly or directly will reduce littering because you are creating value and you don't see money on the street throwing away. When the people realize the waste is not waste anymore, it's valuable, then it's starting to be profitable*" (Informant F). However, the current incentives, in addition to not promoting collection, are also hindering the recycling itself:

"I think the waste management companies are not really incentivized to do any kind of recycling, because they get good money from selling [the plastic] for energy recovery. So I believe in any case, regarding the circular economy, you have to follow the money. If you can't create a situation where the sort of business value is positive, then it's just not gonna work. And that's super important. And you have to balance the scales, so that you don't-, like in this case there is a business value, but it's not for recycling, it's for energy recovery." – Informant A

Clearly, the economics involved in recycling have a crucial role in how recycling for various materials will shape. The interviews highlighted the economic perspectives as an important barrier especially for the recycling of various new bio-based materials which still have a small scale. Informant O pointed out that "*if you think that about half [...] of the plastics used globally are polyethylene and polypropylene, and the share of bio-based materials [...] was it around 1-2% that are bio-based. Their problem is the small scale, [...] and you have to create an economically profitable activity"*. To this end, the recycling of biocomposites, similarly as other more challenging plastics, is largely dependent on the business potential and profitability of recycling them:

"If you think today, biocomposites and also other multilayer materials and dirty materials and all other than the bulk materials have the same challenges. If you think about [recycling], [...] the commercial profitability, that although the technology

exists, so that nothing prevents from recycling biocomposites or technical plastics or multilayer materials, the financial constraints come to play, that it is not necessarily profitable"
– Informant C

For biocomposites, there may be challenges in making recycling profitable due to its more complex structure. According to informant L, "*the more complex the structure [of the material] is, generally the more complex also recycling is, and if it is very complex, it is very difficult to turn it profitable.*"

However, the interviews highlighted that the economic questions in collection and recycling often boil down to the volumes of the material in waste streams. This is eventually what determines how recycling develops for biocomposites, and whether it is possible to manage them as a separate stream (as highlighted previously in Finding 5). Small volumes may prevent the recycling from developing altogether:

"Mostly, the success of recycling, and even in general to begin recycling biocomposites, depends on the amounts that are available. If you have very small amounts of recyclable components, it is not worth it to start recycling them. You cannot make a profitable business out of it. [...] For the recycling of biocomposites to be profitable, the biocomposite streams for recycling should be found somewhere. So it depends on the volumes, and on the other hand, if it is very dispersed, that if you can reach a sufficiently large volume on an European scale, the long transportation distances will become an issue." – Informant R

However, for new materials such as biocomposites to be recycled, the volumes could also be purposefully gathered for the recycling infrastructure to develop:

"In general, I would develop the collection and recycling of plastics to the direction that, at least, the new materials would not be prevented from entering the collection and recycling of plastics, because otherwise there is no way we will ever reach the volumes. That way the volumes could increase, by expanding and diversifying the sources of material [that go to recycling], and not preventing new materials. And exactly the kind of systemic change, that you could for instance [...] join forces and for instance collect all biomaterials to the same pile and make something out of them. Then the volumes may be entirely different and the profitability [...] If you think about these traditional

[recyclers] who recycle polyethylene or polypropylene mechanically, it does not fit into their system, or their commercial model, but there may be opportunities for other actors to build something else." – Informant C

4.3 Disposal routes of biocomposites

Thirdly, the final disposal stages of plastics and biocomposites were discussed in the interviews. As discussed previously in conjunction with Finding 4, the current focus of the plastic industry seems to mostly be on developing recycling. To this end, alternative disposal options beyond recycling seemed less important to the respondents, but they were nevertheless discussed. As potential alternatives, the biodegradation of plastics and carbon storage in the form of biochar were discussed as alternatives for the disposal of plastics. Regarding these topics, two main findings were identified, which are elaborated next.

Finding 7: Biodegradability is currently a problematic approach both for biocomposites and for plastics in general.

In general, the interviews revealed that the plastic industry actors are rather critical towards the development of biodegradable plastics. The critical arguments that were brought up in the interviews aligned mostly with the issues also found in the literature (see 2.2.2).

Firstly, it was emphasized by many respondents that the biodegradability of plastics is generally confusing because many plastics that are labelled biodegradable do not in fact decompose in the natural environment. Rather, most biodegradable plastics nevertheless require industrial composting. This requirement was, however, considered problematic since the infrastructure for dealing with biodegradable plastics in an appropriate way is mostly missing. According to a recycling company's view, the biodegradable plastics "*should go to biowaste. But then [the problem] is that there is not a single industrial composting facility in Europe who could process these [biodegradable] plastics. So, there is easily a greenwashing phenomenon happening, that we picture that we are doing a good thing for the environment, but we are not*" (Informant K). The respondents often mentioned the example of plastic bags used for biowaste, which are labelled biodegradable, but they in fact must be removed from the biowaste stream because their composing time is substantially longer than for the rest of the biowaste. A municipal waste management company, who also operate biowaste composting facilities, described that "*we must remove a lot of the* *biobags, they do not disintegrate in the process and do not have time to decompose, so they instead go to [incineration]. [...] The benefit is maybe a bit lost when it is originally thought that it will decompose. But then it must be incinerated either way*" (Informant M). The issue and procedure are the same also for other plastics found in biowaste, such as biodegradable food packaging that have been on the market for some years.

In addition to the problems that biodegradable plastics cause when mixed in biowaste, many respondents considered them a problem also in the plastic recycling streams. According to a recycling company, "*traditionally, biodegradable plastics affect the mechanical recycling of plastics very negatively, meaning that even small amounts of it [in the stream of conventional plastics] may cause to lose big batches [of recycled plastic]*" (Informant K). Due to the risk of contaminating other recycled plastics, many informants saw it important to separate the biodegradable plastics from the waste stream:

> *"It is again an [additional] plastic type, which is a different plastic type [from the others]. And it is because of its biodegradability in a way very bad in mechanical recycling. So, in a way, if you would like to mechanically recycle that, it should be separated completely. So, it is a problematic material in many ways." – Informant O*

Furthermore, biodegradable plastics were considered challenging from the perspective of consumer behavior. A concern was that households may not know whether biodegradable plastics should be sorted to plastic or biowaste collection, especially if such plastics are problematic in either stream. Furthermore, many respondents identified a harmful effect that "*it still promotes that it is ok to throw [waste] to nature. And that is something we should absolutely get away from. Nothing should be thrown into nature, even though it would be biodegradable. In my opinion, it in a way gives the wrong message*" (Informant E).

From the perspective of sustainability and circular economy, perceptions of the respondents towards biodegradation were mostly negative but also some positive voices were heard. According to informant F, decomposing materials through biodegradation may be positive since it is "*kind of recycling because you are bringing back, let's say, the carbons to the soil, so you are using those compost materials and you can use it in crops, and those crops can be used for producing new materials in general.*" Some also saw the benefit of biodegradable plastics in being safer for the environment, as plastic leakages from production, use, and waste management are bound to happen. Then such leakage plastics or microplastics could potentially biodegrade. However, most of the respondents had a negative view, and saw that the biodegradation approach acts against the efforts of increasing the recycling of plastics:

> *"In my opinion, the best case would be that [plastic] would be recycled as efficiently as possible, to close the loop, meaning to recover it as a material, that would be the most ideal thing. If we now make biodegradable [plastics], it will be away from the circulation, then you will need some new raw material in any case [...]. [It is just about] disintegrating it, and when you decompose the biodegradable [plastic], it will eventually also create CO_2 etc. So, I would see, that it... Luckily it [biodegradability] has a small role at the moment, [...] it in fact represents a single-use culture. That's what it is, in my opinion it is not circular economy in any form, it may be sustainable in some way, environmentally friendly some way, but it is not circular economy in my view." – Informant L*

Generally, it was seen that biodegradability of the material restricts quite a lot in what kind of applications the material may be applied. For instance, many respondents noted that longer term applications cannot have biodegradable materials. However, some respondents mentioned that biodegradability may have its place in some applications if it is considered beneficial functionally.

In the interviews, the respondents were asked whether biodegradability would be a potential disposal route especially for biocomposite materials. It was revealed that purely from the perspective of material properties, the biodegradability of biocomposites could be an attractive approach. According to informant R, the natural properties of the fiber fillers may be beneficial for biodegradability since "*often adding fibers to a biodegradable plastic enhances its degradation*". Thereby, a biocomposite may require a shorter time to decompose compared to just the polymer. Naturally, for the biocomposite material to be biodegradable, the polymer component must be biodegradable. This characteristic may not be the case for many biocomposites currently available, where mostly polypropylene or polyethylene are used as the polymer component.

However, biocomposites do not seem to significantly change the bigger picture regarding the issues of biodegradability. If biodegradability was applied as a disposal approach for biocomposites, it would still require the waste management system to facilitate biodegradability in a such way that the issues discussed before are avoided. The current infrastructure would then need to change, such as by ensuring the appropriate industrial composting or by better separating biodegradable materials from the recycling streams. The interviews highlighted that from a technical standpoint separation is possible, but it is again a question of volume and profitability whether the biodegradable materials are separated from the stream or just rejected instead. It was also pinpointed that biodegradable materials do have the technical capacity to be recycled, but rather the question is whether the system is able to separate such materials in their own fractions and process them appropriately:

> *"[Biodegradable materials] have as good technical possibilities to operate in the [circular economy and recycling] context, as long as the system and the operational context allows it."*
> *– Informant C*

Finding 8: Producing alternative carbon products from bio-based waste plastics is an emerging but yet uncertain approach for capturing and storing carbon.

In the interviews, different carbon capture and storage options were discussed, and in relation, the processing of waste plastics to biochar was discussed as a potential disposal approach. It was rather quickly clear that, in the context of plastics, the biochar approach appeared rather novel and emerging, and many of the respondents hadn't seen such an approach applied to plastics before. Many mentioned it as an interesting possibility, but in-depth perspectives regarding the approach were limited. However, some potential issues were brought up, which are presented next.

Firstly, there was some criticism towards labelling the substance as biochar. As the usual context for producing biochar is to pyrolyze various biomasses directly, such as forestry or agriculture residues, it may be more explicitly called bio-based char, as it includes biogenic carbon. However, for plastics it may not be as clear since it would need to be produced from bio-based plastics. Currently, the traceability of plastic waste streams is not adequate to be able to know what waste plastics are of biological origin. The issue is that "*to call it biochar, you would need to somehow make sure that it is made from material of biological origin only, and that kind of system at least nowadays does not exist*" (Informant L). However, it was also mentioned that arguing about the naming of the material may not be meaningful, because even pyrolyzing fossil-based waste plastics may produce char substances, which might have the same structure and applications as comparable biochar, although it may not necessarily be called biochar due to the possibility of containing fossil-based carbon. The key difference is still that only biochar that contains biogenic carbon can potentially create a negative emission by storing carbon originally drawn from the atmosphere.

Secondly, some interviews highlighted that the synergies between the biochar production through pyrolysis and the pyrolysis-based chemical recycling may not be straightforward. From a technical standpoint, there are many parameters in how a pyrolysis process for waste plastics may be adjusted, ranging from the types of inputs to the temperatures and treatment durations and so on. Often, the process is tuned towards maximizing the output of pyrolysis oils or gases which are substances that can be utilized as chemically recycled material, and minimizing the output of chars. Between these fractions there may be also major quality differences since "*if you make a process that aims for the production of liquids, then the liquids are in principle much higher quality than the chars, and then the char may be of bad quality. Whereas if you are aiming to produce char, then suddenly the char is high quality, but the liquids are bad quality. So, there are challenges*" (Informant S).

As the many parameters of pyrolysis affect how much and what kind of char may result from the process, they also impact where the resulting product can then be used. The qualities of the waste plastic input to pyrolysis seem to have a significant effect on the char outputs and whether the chars will include harmful chemicals or heavy metals. Then, for instance applying biochar to soil amendment or water purification may not be safe. However, some interviews mentioned that more robust alternative uses for biochar could be as a filler substance to cement in construction, or even as a filler to plastics where it could be used in composite materials. However, the potential applications of the biochar substances depend on many factors and may have to be considered case-by-case:

> *"The quality of the char varies so significantly, that almost always, if you have this kind of process, you should start by analyzing the char that you get out, and check the purity, carbon concentration, and heavy metal content. That will restrict and determine where it can be applied. If you have something a bit stronger, then, for example, it could be added to plastic or concrete or asphalt, or some other use where there are already high levels of contaminants, and it won't cause any harm. [...] It is just so radically different. Of course, you can predetermine it, meaning that if you use some raw material masses [for pyrolysis] that do not have any heavy metals [...], then it can be pretty well estimated that the char will be pure, and it may be applied for instance to soil amendment [...]. Because no external substances enter the material during pyrolysis, it is just what is al-*

ready in the material. But if the raw material has some contaminants, some contaminants may be also removed through pyrolysis, for instance to the gas or liquid fraction, which is when it is removed from the char. But it is very case-by-case." – Informant S

The interviews aimed to uncover how the biochar approach could fit especially for biocomposites. Generally, this was a difficult area for the respondents to assess, but at least one informant estimated that biocomposites could fit biochar production rather well:

"In fact, a biocomposite would fit better into this type of recycling, this biochar production, than any regular plastic. If there is for instance a wood-based biocomposite, which does not include a lot of contaminants, it could be well made into a high-quality biochar in the end of its lifecycle." – Informant S

As for the biochar approach in general, it was reflected in the interviews that the respondents again mostly saw recycling as the primary goal. Many were skeptical that if pyrolysis is applied to waste plastics, why would the goal not be to chemically recycle the plastic and rather produce biochar. Still, the biochar approach could be better than incinerating plastic, as the approach would prevent the embedded carbon from being released to the atmosphere in burning:

"I think it's important to have different solutions for different scenarios and I think this biochar is a good one, but it's still at the bottom of the pyramid. [...] If you've created something, if you've spent energy to create something, like a plastic, regardless of whether it's from a biobased source or not, then using it for that or something close to that is the best thing to do for as long as possible, because that's also sequestering. I mean, you're also just keeping the carbon in the material. So, I see that carbon sequestration only as one step above energy recovery in some cases." – Informant A

Finally, it was discussed that biochar production may not be the only possible method to capture and store carbon. Many of the respondents saw long-term applications of plastics as storing carbon, and that essentially recycling also stores carbon in the plastic material as it is not released through burning. Furthermore, some respondents mentioned a future scenario where carbon could, in fact, be captured from incineration facilities. With the potentially higher availability of pure hydrogen in the future, such captured carbon could be combined with hydrogen be a potential artificial source for hydrocarbons usable in plastic production. However, this was pictured as a very long-term vision, and something like biochar production could work as a medium-term solution for capturing and storing carbon:

> *"We may think, that will we in the long run only use the [incineration] route that everything is burnt. Probably not everything, but let's say that you wouldn't have to care. Burn it, and capture the carbon dioxide. Then you have the hydrogen economy. There will be limitless hydrogen. [...] Capture all hydrogen. Produce it back to [hydrocarbons] and input into plastic production. [...] We could go back to not caring. We burn, because we can capture [the carbon dioxide] and use it again chemically. But this is sometime during the lives of my kids or grandkids." – Informant E*

4.4 Systemic implications of biocomposites

The findings presented thus far have concerned especially different lifecycle stages and what implications biocomposites have in them specifically. However, the interviews revealed also some more systemic issues regarding biocomposite materials regarding the overall sustainability of the material. These systemic issues are presented as one main finding next.

Finding 9: Biocomposite materials may offer sustainability benefits even though they are more challenging in the current recycling system.

The interviews revealed an interesting contradiction regarding the sustainability of biocomposites. As discussed previously in Finding 4, it was often reflected in the interviews that the plastic industry currently sees recycling as the most important area in the industry's efforts to become more sustainable. To this end, it was natural to see resistance towards biocomposite material, which many of the informants saw to act against the improvement of recycling. Informant L highlighted the central conundrum regarding biocomposites:

> *"When [the industry] tries to make the circular economy work, it would be ideal to simplify structures rather than make them more complex. This goes a bit to the other direction [...] one part is that you get some bio-based components in, 10, 20, 30% biocomponents in, but is it a good thing from the larger perspective if you cannot really recycle it?" – Informant L*

It could be determined that many of the industry actors see only focusing on the bio-based content of materials as some sort of sub-optimization if it contradicts with the recyclability of the materials. In this sense, many saw that it would be better to develop bio-based polymers instead of mixing bio-based fibers into plastic in biocomposites:

> *"The biocomposite makes [the recycling] worse. [...] I would rather have a bio-based feedstock [to plastic production], because the recycling part will be very challenging with a biocomposite especially. I see that better would be if you can for instance replace the plastic product with cardboard or something, it is okay even though it is away from [the business of the plastic industry]. From the perspective of recycling or circular economy it is okay, but to mix [plastic with fibers] I do not see anything positive about it. Of course, now you can advertise that this has replaced fossil-based [material] by 20% of bio-based component, but it is a bit of greenwashing. [...] It can be that previously the 100% could be recycled, but now the material where you have 20% biocomponent cannot be recycled. The outcome may not be better from the environmental perspective, it may be worse. [...] We see that it is only brought [to the market] with the angle that now fossil-based [materials] are replaced."*
> *– Informant E*

However, many respondents also saw it important in the larger perspective that the current state of recycling is very limited. The recycling rates are across Europe stuck at around 30%, and mostly only packaging plastics are recycled, which incidentally may not be a likely application area for biocomposites (see Finding 2). To this end, the arguments against biocomposites may lose some ground as they are based on the negative effects to recyclability. Instead, the resistance for biocomposites may mostly originate from the interests of the recyclers which may not reflect benefits in a holistic perspective:

> *"[The industry] leans on all plastic being now recycled, but in reality, it is not, it is still a small fraction of plastics that currently circulate and in a very limited manner. [...] Also the regulations in EU about recycling targets start to guide towards forgetting all innovative materials, that soon you would be making everything from polypropylene and polyethylene, to make them circulate, and because the plastic industry is a bit conservative and also the waste processing industries, of course they would like [...] it would be easiest [for them] if they would*

get only polypropylene, they wouldn't need to sort or do anything else, but the new innovative materials, new solutions, should also be remembered, and not just be stuck with the easy, good and old." – Informant C

Therefore, in the current operating space where recycling is still rather limited, it is possible that biocomposites could bring sustainability benefits. However, it may not be a solution in the longer term if recycling is improving, because then the negative effects to recyclability may grow to be substantial:

"Sometimes you can get benefits, like if you do a realistic LCA calculation, the benefits you get from using a biocomposite, even if it's incinerated, can actually outperform a plastic, if it's only recycled two or three times and only 40% of it is recycled, which is the kind of reality where we're at today. So, you can really, if the customers are realistic about what's actually happening, and not just focusing on is it recyclable or not, then you can still get sustainability benefits out of using a biocomposite in those applications, but it's not something that we're actively really pushing because it's not a long-term kind of solution for our material. But it can have sustainability benefits in the current environment today, because the recycling rate for plastic is so low." – Informant A

4.5 Summary of the findings

In this chapter, the findings of the interviews have been presented and discussed. In total, nine findings were discovered from the empirical data, which are summarized below in Table 12.

Table 12: Summary of the main findings of the interviews

Theme	**Finding**
Material choice and production	1. The adoption of biocomposites is mostly driven by the valorization of side-streams and improving carbon footprint of the material by increasing bio-based content.
	2. Biocomposite materials are limited in where they can be applied but are more likely beneficial in longer life non-packaging applications.
	3. The production and supply chains of biocomposites have drawbacks compared to conventional plastics, which hinder the adoption of biocomposites.
Biocomposites in plastic recycling	4. The current recycling system of plastics discourages the adoption of biocomposites.
	5. The current plastic recycling infrastructure would require changes to accommodate biocomposite recycling.
	6. The economics of recycling dictate how the recycling system may accommodate biocomposites.
Disposal routes of biocomposites	7. Biodegradability is currently a problematic approach both for biocomposites and for plastics in general.
	8. Producing alternative carbon products from bio-based waste plastics is an emerging but yet uncertain approach for capturing and storing carbon.
Systemic effects of biocomposites	9. Biocomposite materials may offer sustainability benefits even though they are more challenging in the current recycling system.

5 Discussion

In this chapter, the thesis aims to answer the research questions (established in 1.2) based on both the evidence from the empirical findings and the reviewed research literature. In the following sections 5.1–0, the three sub-questions of the main research question are addressed. In 5.4, an answer is sought to the main research question based on the findings to the sub-questions and generally the findings from the empirical findings and findings from research literature. After this elaboration, the chapter discusses the implications of the research results to different stakeholders in section 5.5, including companies operating within the plastic value chain, policymakers, and the contribution the study makes to the research community. Finally, section 0 evaluates the limitations of the study and identifies avenues for future research.

5.1 Biocomposites as means to increase bio-based content in plastics

Sub-question 1	**Related findings**
How can biocomposites increase bio-based content in plastics?	Finding 1 Finding 2 Finding 3 Finding 4 Finding 5 Finding 9

This thesis has studied whether biocomposite materials could be a viable approach in increasing bio-based content in plastic materials. Thus far, the efforts of substituting fossil-based materials with bio-based materials in plastics have mostly relied on developing polymers from bio-based feedstocks to replace fossil-based polymers. However, the adoption of bio-based plastics has so far been rather marginal (European Bioplastics, 2023). Some main issues related to the adoption of bio-based plastics were identified in the research literature. Their higher prices and often inferior mechanical properties make it difficult for them to compete against fossil-based commodity plastics (Acquavia et al., 2021; Fredi & Dorigato, 2021). Furthermore, the bio-based raw material often relies on crops that can also be used for food purposes, and therefore using these crops for plastic production may cannibalize food production, as well as significantly increase land and water use if fossil feedstocks would be substituted with bio-based feedstocks in a larger scale (Rosenboom et al., 2022).

To this end, biocomposite materials appear to offer potential solutions. Biocomposites may substitute fossil-based material in plastics with a different approach, as bio-based natural fibers are blended into plastic materials rather than producing the plastic itself from bio-based feedstock. These fibers may be sourced from various side-streams, and as such they would not cannibalize food production or increase land use (Mohanty et al., 2018). In addition, the side-stream natural fibers are generally considered abundant and very inexpensive, which could potentially address the price issues of bio-based plastics, and they may also introduce a reinforcing role to the material which could improve the material properties (Mahmud et al., 2021; Sanjay et al., 2018). Against this background, the thesis set out to research the viability of biocomposites in possibly solving these challenges of bio-based plastics and thus providing an alternative approach in increasing bio-based content to plastic materials.

Generally, the research revealed that, although they seem promising in some respects, biocomposites do not drastically overcome the barriers that bio-based plastic materials have for their adoption. In fact, biocomposites create some problems of their own. Firstly, it seems that biocomposites are still substantially more expensive than fossil-based plastics. Although cheap fiber materials may be used, the limited scale, production process drawbacks, and the need to apply more energy still seem to increase the production costs so that no significant cost benefits are achieved compared to bio-based polymers (see Finding 3). This makes it unlikely that biocomposites would significantly change material decisions, which currently favor the cheap fossil-based plastics, any more than bio-based plastics. However, there may be premium applications, where the natural look and feel of biocomposites may create value favorably (Manu et al., 2022) and thereby could overcome their higher price (see Finding 2).

Secondly, the research found evidence that the introduction of natural fibers to plastic does not significantly improve such material properties that truly matter in the practical material decisions for products. The literature review revealed that a lot of investigations have been made in material science to engineer properties of biocomposites, but generally the interviewed industry actors did not see the properties of biocomposites so favorable that they would be adopted more. On the contrary, the interviews indicated that the properties of biocomposites restrict rather much where they can be applied (see Finding 2), which was also indicated in research literature (e.g., Mahmud et al., 2021; Manu et al., 2022). Therefore, there is, in principle, a rather limited space of potential products where the biocomposite approach could provide sustainability benefits without compromising the functionality of products. Nevertheless, it was found that possibly viable applications for biocomposites may exist in less demanding and longer life applications outside packaging contexts, such as various consumer products.

Thirdly, however, a positive factor for biocomposites were indications both from research literature and the interviews that biocomposites indeed can utilize waste or side-streams to source the natural fibers into the materials. The valorization of side-streams was found to be a central driver for the development of biocomposite materials by the producers that were interviewed (see Finding 1). Moreover, it was often mentioned in literature that the natural fibers may come from side-stream sources (e.g., Mohanty et al., 2018). Thereby, it seems that biocomposites can be better than bio-based polymers since they have the capacity to increase bio-based content in plastics without having harmful effects to cannibalizing food production or drastically increasing land use. However, sourcing natural fibers from waste or side-stream resources may be a limiting factor in the long-run because such sources are eventually bounded and sourcing from them is seen complex (see Finding 3).

Finally, a central drawback for biocomposites was that, in practice, their recycling is problematic. Although the literature indicated that biocomposites may be recycled (e.g., Mahmud et al., 2021; Soroudi & Jakubowicz, 2013), such notions mainly considered a technical standpoint and not the practical abilities of the recycling infrastructure to recycle them. In the interviews with industry representatives, this practical view on the recyclability of biocomposites was substantially more negative. Mostly, the interviews indicated that blending fibers into the plastic practically destroys the recyclability of the material in the practical recycling context (see Finding 4). Because of this, it seems that from the industry’s standpoint it is more favorable to increase bio-based content in plastics by bio-based polymers rather than biocomposite approaches, since at least drop-in bio-based polymers could be recycled within the current recycling streams. However, this conclusion is clearly not based on the drawbacks of the biocomposite material itself but rather based on how the current recycling infrastructure is organized. Thereby, it might be possible for biocomposites to be recycled if appropriate changes are made to the infrastructure, because biocomposites still have the technical capacity to be recycled (see Finding 5).

Generally, it could be reflected in the interviews that some industry actors wanted to challenge the whole objective of aiming to increase bio-based content in plastics. To different degrees, many industry representatives emphasized the importance of recycling in the efforts of decreasing the use of virgin fossil feedstocks. Many thought that it is partial optimization of sorts if some actors aim to bring materials to the market that are labelled sustainable only because they have bio-based content. There were arguments that bio-based content does not by itself imply that the material is sustainable, but rather it is also important whether the material is recyclable and, even more importantly, where it actually will be recycled in the operational recycling system. On the other hand, there were also opposing views that it might be possible for biocomposites to create sustainability benefits by purely increasing bio-based content even though it may have negative impacts to the practical recyclability of the material (see Finding 9). This conclusion is possible at least currently, when the plastic recycling systems in general are still limited, and it is, in fact, more likely that a plastic product that is produced will not be recycled than it to be recycled, irrespective of what specific material it is (this conclusion is safe to make as recycling rates around Europe are at about 30%, and recycling mostly concerns plastic packaging only). Therefore, perhaps, there may be some truth in considering only the bio-based content in material choices. Incidentally, considering just the bio-based content was identified as a central driver in why biocomposites are considered in the first place (see Finding 1).

There were also indications that confusions regarding labelling something as 'bio' may have a part in creating skepticism towards biomaterials within the industry. In the interviews, many industry representatives wanted to make sure that when we are discussing biomaterials, we know what we are meaning. Related to the meanings, it was disturbing to notice that a widely accepted definition for bioplastics encompasses either or both bio-based origin and biodegradability (see 2.2.1), which have two entirely different meanings: the former concerns the raw materials that have been used in creating the plastic, and the latter is rather a way to dispose of the plastic. It felt that many industry representatives were skeptical towards bioplastics already because of the confusing nature of the definition and how impressions easily mislead consumers into a possibly false sense of sustainability of the materials. Thereby, in the context of plastics it seems important to rather not talk about 'bioplastics' but rather about 'bio-based plastics' if the purpose is to mean substituting fossil-based raw materials.

To conclude, it seems unlikely that biocomposite materials would provide a panacea for the plastic industry's adoption of bio-based materials. Even though biocomposites may be beneficial from a sustainability point-of-view in some cases, they are still struggling to compete against fossil-based plastic alternatives because of their higher prices and issues with properties. These pitfalls, nevertheless, make them an option in only a limited area of current plastic applications. Instead, bio-based polymers may have higher chances of being adopted in a wider range of applications. Moreover, they may substitute fossil-based feedstock without compromising recycling within the current infrastructure, at least if bio-based drop-in plastics are considered. Nevertheless, the competitiveness issues between bio-based plastics and fossil-based plastics remain to be solved.

5.2 Biocomposites as part of the circular economy of plastics

Sub-question 2	**Related findings**
How can biocomposites contribute to the emerging circular economy of plastics and extend the service life of plastic materials?	Finding 2 Finding 4 Finding 5 Finding 6 Finding 8

From views found in both the background literature and the interview discussions, it is safe to say that the ongoing transition to a circular economy is perhaps the largest systemic change ever in the plastic industry. Against this background, although biocomposites may have their role in increasing the bio-based content of plastics, they would also need to fit the larger vision of a circular plastic economy. This suitability for circularity was especially an area that had been investigated only to a limited degree previously, so bringing more understanding into this area was one of the main objectives of this study.

Generally, it seems that developing the recycling of plastics is the main spearhead of the efforts that the plastic industry sees within transitioning to a circular economy. Recycling has so far been mostly done with mechanical recycling, but chemical recycling technologies are emerging as an enabler to transform the recycling operations (see 2.4.2). An important factor in recycling is also the development of the collection and waste management system around waste plastics, which has an important role in facilitating high-quality recycling (Fredi & Dorigato, 2021). Whereas plastic waste has so far mostly been collected in a mixed principle, to increase recycling rates and the quality of recycling in the future it may be required to employ more separate collection schemes that enable small loop or closed loop recycling (see 2.4.3). Against this background, previous research literature was rather limited in how biocomposite materials could fit into recycling. The literature mostly considered technical perspectives, stating more the general notion that biocomposites are thermoplastic materials that may be melted and reused as recycled material (e.g., Mahmud et al., 2021; Soroudi & Jakubowicz, 2013). However, the literature left it mostly unclear how biocomposites could be recycled in practice in the existing recycling infrastructure.

The interviews in industry revealed that, generally, it is very unlikely for the current infrastructure to recycle biocomposites (see Finding 4). There are significant limitations, as the current recycling operations focus only on high-volume conventional plastics, which they can somewhat profitably recycle mechanically. Especially in mechanical recycling, it seems that it is crucial to know what the plastic waste material contains, and in the current mixed approaches of waste collection this relies on automatically sorting specific types and qualities of waste plastics from the stream. As biocomposites are still very low in volume in waste streams, it is unlikely that mechanical recycling operators would separate them from the mixed stream to recycle them, although biocomposites are technically possible for the automatic sorting technologies to identify. Rather, they are mostly seen as something else than the high-volume commodity plastics and will therefore be rejected from the stream and incinerated. However, the situation could be different if there were higher volumes of biocomposites in the waste stream, and it might be possible to separate and recycle them profitably (see Finding 6). In this case, there are still drawbacks for biocomposites since they may be complex to manage due to the diversity of plastics and natural fibers that biocomposites may contain. A solution could be to employ small loops, such as by collecting specific biocomposites through separate collection schemes, and thereby controlling them as their own stream to recycle them in high quality (see Finding 5). Otherwise, in the current operating environment, it is very difficult for new materials with small volumes, such as biocomposites, to be recycled.

An uncertainty for the future is still the development and adoption of chemical recycling. In theory, chemical recycling is considered as a recycling technology that could allow more mixed and challenging waste plastics as input (Fredi & Dorigato, 2021). However, some interviews indicated that the chemical recycling technologies may still require rather pure waste plastics as raw material, at least while they are still being developed. As chemical recycling encompasses various technologies, the appropriate technology may have to be chosen based on the plastic polymer type that the process aims to recycle (Fredi & Dorigato, 2021). Therefore, it may be that even chemical recycling may not be able to completely avoid the need to sort waste plastics per type. For new materials with small volumes, such as biocomposites, chemical recycling may not then solve the recycling issues either. However, there is still substantial uncertainty in how different materials would fit into chemical recycling, and therefore the interviewed industry representatives still had a rather limited knowledge in how biocomposites could be chemically recycled. In the interviews, there was one informant from a company developing chemical recycling who indicated that the fibers in biocomposites may generally be a negative thing in pyrolysis as they are considered as an impurity from the process perspective, and as such may reduce the yield of pyrolysis oils and gases from the process.

In conclusion, because the recycling infrastructure is limited, biocomposites are generally excluded from the circularity of plastics at least in the short term. Therefore, their capacity to extend the lifecycles of materials in general is very limited. However, in the longer term, it is not impossible for biocomposites to be recycled, but it would require changes in the infrastructure, such as adopting small loops. The increase of the volumes of biocomposites in the waste streams may also gradually make it more attractive to start separating and recycling them. Still, these developments are likely to take a long time, and would need to be facilitated by, for instance, expanding the recycling system to also other areas of plastic use than packaging (see Finding 5).

If circular economy is considered in more broad terms, however, biocomposites might have a role that could fit the larger picture. As was identified in Finding 2, biocomposites are more likely to be applied in plastic products that are meant to last longer, rather than in single-use packaging. This finding is rather well aligned with the general strategies of circular economy, where it is imperative to extend the lifecycles of products (see 2.3.3). Then, perhaps biocomposites could be aligned with the broader circular economy of plastics, if they encourage to design and produce products that are meant to last longer. Furthermore, long-lasting bio-based products could store atmospheric carbon in them, which is beneficial from the sustainability standpoint (see Finding 8 and Stegmann et al., 2022). Finally, as biocomposites may utilize different side-streams from forestry or agriculture, for example, they also connect to the circular economy development of other industrial sectors than the plastics sector. As such, it may be seen positive for the general development of the circular economy that biocomposites may, in a way, recycle or repurpose side-streams from other industries that would otherwise be wasted.

5.3 End-of-life strategies for biocomposites

Sub-question 3	Related findings
How can biocomposites limit emissions and plastic waste from plastic disposal, and promote carbon capture and storage?	Finding 4 Finding 7 Finding 8

As only a limited share of plastics is recycled in the current infrastructure, different disposal strategies have a crucial role for the environmental effects of plastics. The use of plastics creates plastic waste, which currently has a high likelihood of leaking to the environment and contaminating natural ecosystems if not appropriately managed (see 2.1.4). Furthermore, waste disposal often creates GHG emissions as plastic incineration is becoming increasingly popular around the world (see 2.4.4). To this end, previous research was very limited in how the use of biocomposite materials instead of conventional plastics would affect these outcomes.

From the perspective of waste biocomposite materials, the best disposal strategy from the sustainability standpoint would be, naturally, to recycle them (Sommerhuber et al., 2017). However, as has been established in this thesis, biocomposite materials are challenging in the current recycling processes. Therefore, it is very likely that waste biocomposite materials are rejected and incinerated (see Finding 4), which releases emissions. As such, biocomposites may increase emissions at the stage of waste disposal compared to conventional plastics whose likelihood of being recycled is higher. However, there may be reasons why burning biocomposites might not be a major problem. Biocomposites contain a high concentration of bio-based material because of the natural fiber component, and possibly even fully bio-based content if bio-based plastic is used in them (Mohanty et al., 2018). The embedded carbon originates then to a large degree from the atmosphere, which is released back in the process of burning. One might therefore consider that burning such material is carbon neutral, unless there is a great share of fossil plastic involved. However, the carbon neutrality of burning biomasses is a widely disputed assumption in the research community, and conclusions regarding it should be made with caution (Booth et al., 2020).

To deal with plastics leaking into the environment, biodegradability has been offered as a potential solution. If biodegradable plastics were more widely adopted, it would offer a new disposal route for plastics and possibly the plastic leakages would cause less harm to the environment (European

Commission, 2018). However, it is apparent from both research literature and the industry interviews that there are large problems related to biodegradability. The problems that were discovered in the research literature were very well aligned with the problems that the industry representatives pinpointed in the interviews (see 2.2.2, 2.4.4, and Finding 7). One of the main problems was that, although some plastics are labelled biodegradable, they do not in fact decompose in natural environments and would instead require industrial composting. The interviews indicated that, on the other hand, such capacities for industrially composting plastics do not seem to exist. In addition, there were many concerns that biodegradable plastics could contaminate recycling streams, or that they could increase the behavior of throwing plastic waste to nature even though they might not decompose in the open environment.

It seems apparent from the results, that regarding the issues of biodegradability, little can be achieved by just considering the theoretical biodegradability of the material. Rather, the whole waste management system would need to change for it to facilitate biodegradability better. Therefore, considering biocomposites as an alternative material to conventional plastics does not seem to change the problems of biodegradability to any significant degree, as biodegradability is considered problematic with all plastic materials in the current setting. There were some indications that the fibers in biocomposites could enhance the biodegradability of the material to some degree, but this seems irrelevant in the larger perspective where the issues of biodegradability in the wider system remain.

In the stage of final disposal of plastics, this thesis also explored opportunities for carbon capture and storage. In this stage, a method for storing carbon was identified by producing biochar from bio-based waste plastics through pyrolysis. Surprisingly, it seems that the process of producing biochar with pyrolysis has mostly been investigated only with different biomasses as the input, and, to the author's knowledge, literature on using this approach for waste plastics is very limited. A rare example found is Igalavithana et al. (2022). In the interviews with industry representatives, there was also substantial novelty to this approach, which also resulted in very limited statements about its viability. Generally, producing biochar was considered as something that could possibly be done rather than incinerating plastics, but it was still seen secondary to recycling, which was seen as the primary objective that should be developed (see Finding 8).

The interviews also aimed to explore how the biochar approach could be applied to biocomposites especially. As the approaches are novel, there was very limited perspective from the interviews into how biocomposites could fit into the biochar production route. However, one informant from a company investigating chemical recycling through pyrolysis indicated that in such processes the fibers may cause to lose yields of pyrolysis oils and liquids. One might determine, then, that this would mean that the pyrolysis process outputs more chars if fibers are present in the input. This seems aligned with the review by Al-Rumaihi et al. (2022), whose results indicate that co-pyrolyzing plastic with biomass generally optimizes the process more towards char yield than the yield of liquids and gases. Therefore, there may be an opportunity in the pyrolysis of biocomposites for biochar production. However, there remains a question whether there can be synergies between the chemical recycling of plastics via pyrolysis and biochar production. Although they are both based on similar technology, the pyrolysis process may be very different based on what the process aims to produce (see Finding 8). These synergies, as well as the biochar approach in general, would require further investigation. However, such approaches could open alternative avenues for biocomposites to be recycled to other products than plastic materials, if it would be determined viable to produce biochar or other carbon products from biocomposites. Biocomposites could then potentially have a secondary life as a carbon product such as biochar, having various practical applications in addition to possibly acting as a carbon storage (see 2.4.4.3 and Finding 8).

To conclude, it seems that biocomposite materials offer only limited possibilities to change the outputs of the plastic economy compared to conventional plastics. Because of the pitfalls of the current waste management and recycling system, it is still relatively likely that plastic use will result in harmful outcomes to the environment in the stage of final disposal, irrespective of whether biocomposites or conventional plastics are considered. Harmful emissions are likely to be created still in the future from plastic incineration, which might be a slightly more likely fate for biocomposites. Plastic waste is also likely to keep leaking to nature, which will remain harmful as the industry is reluctant to adopt biodegradable plastics. Even if they were adopted, biodegradable plastics might still not solve the negative environmental effects of plastic leakage if they do not degrade in the open environment in the first place. Producing other carbon products from waste plastics could provide methods that could store the embedded carbon in plastics for a long time, but the approaches still have a lot of uncertainty. Perhaps, the plastic industry could aim mostly for keeping the carbon either in circulation by drastically increasing recycling or keeping the carbon in use in long-life plastic applications. The latter of these approaches might be the best short-term approach for biocomposites especially (see Finding 8).

5.4 Towards a systemic perspective – The role of biocomposites in an environmentally sustainable plastic economy

In the previous sections, the chapter has sought answers to the three sub-questions of the research study. The sub-questions considered in more depth how biocomposite materials impact different stages of the lifecycle of plastic use. In this section, based on the results of the sub-questions, the empirical findings in general and the literature review, the thesis analyses the results regarding the main research question.

Main research question
How can biocomposite materials contribute to the environmental sustainability and circular economy of plastics across the plastic value chain?

To seek answers to this question from a systemic perspective, the open system transformation model of the plastic economy (introduced in 3.2) is employed as a conceptual approach in structuring the plastic economy system and understanding how biocomposite materials change the systemic picture. The system model, along with the main results of the analysis, are presented below in Figure 8.

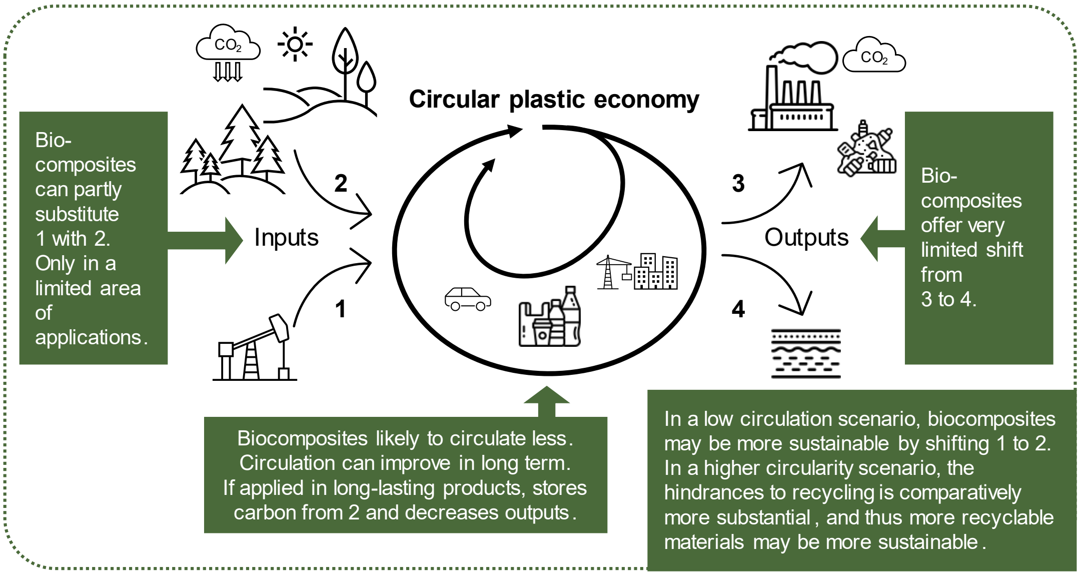


Figure 8: Biocomposites in the open system model of plastics

The main background premise of the study is that the current plastic production, usage, and disposal compose an unsustainable plastic economy system. As identified in 2.1.3, most plastics are produced from fossil-based feedstocks, and bio-based inputs represent only around 1,5% of produced plastics (Plastics Europe, 2022a). Furthermore, the recycling rates for plastics are rather low: for instance, in Europe the recycling rates are at only around 30% and recycling mostly concerns packaging plastics only (see 2.4.3 and Finding 4). Finally, plastics are disposed of in ways that create environmentally harmful outcomes, such as by incinerating them, which creates GHG and noxious emissions, or by landfilling them which has a high likelihood of plastic waste leaking and contaminating natural environments (see 2.4.1 and 2.4.4.1). The problem can be illustrated with the model as follows. The plastic economy mostly takes carbon from fossil depositories (input flow 1), keeps carbon in the circulation within the plastic economy in a very limited degree, and, in the end, releases the carbon either to the atmosphere through incineration, or dumps it to the environment in harmful forms (output flow 3). Given that the demand for plastic materials is constantly increasing (see 2.1.2), the plastic economy system is a machine that effectively pushes fossil carbon into the atmosphere.

As discussed in 3.2, a transition towards environmental sustainability of the plastic economy could be seen to require any or all of the following changes: minimizing the input of fossils (flow 1), maximizing the input of bio-based feedstocks (flow 2), extending the service life of materials within the plastic economy by increasing circulation (keeping carbon in the economy), minimizing harmful outputs (flow 3), and maximizing the relative output into carbon storages (flow 4). For biocomposite materials to be beneficial from the perspective of environmental sustainability, it can be determined that they would need to offer some of these positive changes compared to the current fossil-based plastics, and possibly also do them better than bio-based plastics. These changes are evaluated next.

Firstly, biocomposites can provide some benefits related to the inputs to the system. The biocomposite approach can indeed shift inputs by substituting fossil-based feedstock by bio-based material in plastics (Mohanty et al., 2018), thereby reducing flow 1 and increasing flow 2. Because of this alone, biocomposites can be a more sustainable alternative than fossil plastics (e.g., Civancik-Uslu et al., 2018; Haylock & Rosentrater, 2018; Kamau-Devers & Miller, 2020). Moreover, as discussed in 5.1, biocomposites can do this input shift by less impacts on food production cannibalization or land and water use increase compared to bio-based plastics, as they mostly utilize various side-streams as the bio-based content (see Finding 1). However, a limitation is that biocomposites can offer these sustainability benefits in only a limited area of applications because value chain actors do not see them suitable for a wide spectrum of uses due to their drawbacks (see 5.1).

Secondly, however, in the circularity of the plastic economy biocomposites present themselves negatively compared to current fossil-based plastics. As has been demonstrated in this study (see 5.2), it is seen as a major handicap for biocomposites that the current recycling infrastructure cannot recycle them (see Finding 4). Considering extending the service life of plastic materials by increasing circulation, biocomposites may then act against improving sustainability. However, the recycling of biocomposites is not impossible, but it would require accommodation from the recycling infrastructure (see Finding 5). Finally, if it is considered that biocomposites would mostly be applied to long-lasting products, then they may in fact positively impact the service life extension of materials and thereby sustainability.

Thirdly, biocomposites seem to offer very limited changes to the mix of outputs from the plastic system (see 0). Based on the findings, biocomposites are likely to remain creating harmful outputs similarly as conventional plastics, through plastic leakages or emissions via incineration. Compared to fossil plastics, biocomposites may even create somewhat more output altogether, as they are more likely to end in incineration due to the recycling hindrances, thereby relatively increasing the harmful outputs (flow 3). This can be a factor that again acts against sustainability, but making this conclusion may not be fully clear. It might be argued whether the recycling of fossil-based plastics really avoids some outputs or merely delays the output (Geyer et al., 2017), in which case the biocomposites may not compare as negatively. Finally, the incineration of biocomposites may be less harmful since they partly return bio-based atmospheric carbon to the atmosphere, but this conclusion should be made with caution (e.g., Booth et al., 2020).

Moreover, biocomposites can very limitedly shift final disposal patterns towards long term carbon depositories (see Finding 8). These questions seem to be beyond the specific material choices, and rather more fundamentally connected to the practices of plastic waste management. The findings suggest that the plastic industry is currently more focused on accelerating recycling and does not consider the systemic importance of disposing carbon embedded in plastics to long term depositories of carbon. It seems that there may be untapped potential for new approaches of storing carbon for the long term, such as by processing bio-based plastic to biochar.

As an overarching conclusion, the findings of the study indicate that the comparative sustainability of biocomposites depends much on the degree to which the alternative material, fossil-based plastic, is being recycled. If one considers a scenario where plastics are not recycled at all or recycled only little, shifting any inputs from fossil carbon sources to bio-based carbon sources can improve sustainability of the material (given of course that acquiring carbon from bio-based sources does not create sustainability problems of its own). In this low-recycling case, there is evidence that materials like biocomposites can be a more sustainable choice than fossil-based plastics (see Finding 9). However, in a scenario where plastics would be recycled to a very high degree, bio-based inputs are still better than fossil-based inputs, but the sustainability benefit depends also on whether the shift from fossil to bio-based input sacrifices the recycling of plastics. In this high-recycling scenario, introducing biocomposites may not bring sustainability benefits since even though they on one hand increase bio-based content of the material, they practically prevent the material from being recycled in the system on the other hand. More recyclable bio-based materials would then be more sustainable, and bio-based input could be more beneficially added to plastics via drop-in bio-based plastics which can be recycled among the fossil-based plastics (see Finding 4).

Currently, the degree of recycling is somewhere between the low and high recycling scenarios, perhaps even closer to the low recycling scenario due to limited recycling rates (see Finding 4). Furthermore, there are great differences globally, with some countries much more advanced with plastic recycling than others (Plastics Europe, 2022a). Even in economies where plastic recycling is more advanced, such as in Europe, there are also market segments where recycling is still virtually non-existent, such as non-packaging applications in the case context of Finland (see Finding 4). Therefore, it appears to be dependent on these factors related to the operating environment whether biocomposite materials are a good approach to move towards sustainability. The benefit from biocomposites may be very limited or even negative in packaging applications in relatively high-recycling operating environments, but the benefit may be more significant and positive in low-recycling market segments and countries.

This thinking demonstrates the main conclusions of the study. To eventually disentangle the negative environmental effects of plastic use from the continuously growing global demand for plastics, the sustainability of plastics will require both a transition to bio-based feedstocks and a radical increase in circular economy practices (Palm & Svensson Myrin, 2018). Biocomposites may be an approach that pushes the sustainability of plastics in the right direction. However, it seems that biocomposites may be a solution only in the short-to-medium term and only in a limited area of applications where they are suitable as a material choice. As the recycling of plastics is generally still in its infancy and nevertheless limited even though done in some contexts, biocomposites may bring sustainability benefits by substituting fossil-based material with bio-based material, even though they are likely incinerated after first use and not recycled (see Finding 9). In the short term, the sustainability of biocomposites may also be improved by applying them in long-lasting applications, where they can offer carbon storage.

However, in the medium-to-long term as the recycling of plastics expectedly increases and expands to new segments, the hindrances to recycling and the complexity of biocomposites are likely to arise as a barrier. Generally, it seems that less complex material structures are favored as they are easier to recycle. It may then be more viable to introduce bio-based content in plastics by making plastics from bio-based feedstock, as this approach could compromise recycling less, rather than embedding the bio-based content into the material in the form of a natural fiber. However, the problems of bio-based plastics increasing land and water use and cannibalizing food production still remain. Therefore, it seems that also other actions are needed, such as drastically decreasing the absolute volume of inputs needed in the plastic economy. For this, something in our way of consuming plastics must change to decrease the consumption of plastics, such as a radical increase in recycling or other circular economy practices, like to reuse plastic products or refusing of their use entirely in some contexts. Nevertheless, biocomposites may still have a role in some hard-to-recycle segments and applications also in the longer term, as well as by diversifying the raw material base for plastic materials. Neither is their recycling impossible in the long term, but it would require the usage volumes of biocomposites to increase and recycling practices and technology to develop to make their recycling profitable.

To conclude, the findings of the study indicate that the implications of biocomposites on the transition of plastics towards more sustainable practices are limited. Biocomposite materials can create sustainability benefits in some circumstances. However, given the constraints that the materials are facing when applied to the practical operating environment, and the interests of different actors in the plastic value chain, the benefits that can be gained by adopting these materials appear rather limited. In the short term, however, the materials can be a starting point for seeking alternatives to conventional fossil-based plastics.

5.5 Implications to stakeholders

The previous sections have sought answers to the research questions of the study. In this section, it is discussed what implications the results of the study have for the most relevant stakeholders in the plastic economy. The considered stakeholders are the companies operating in the plastic industry value chain and policymakers that regulate the industry. Also, the section explores the theoretical contributions that this study offers to research literature.

5.5.1 Implications to the plastic industry and value chain

In the conducted interviews with the plastic value chain actors, the general attitude towards biocomposites was critical. As has been discussed, a major reason for this criticism is the hindrances that biocomposites have in the practical plastic recycling environment. However, companies operating in the plastic value chain could have benefits from applying biocomposite materials on some occasions.

In the short term, there seems to be no absolute blockers to why biocomposite materials could not be applied in plastic products. These materials can have sustainability benefits since they have the capacity to substitute fossil-based plastic (Kamau-Devers & Miller, 2020; Shanmugam et al., 2021). However, it would need to be considered whether biocomposites are suitable for the application in question, and in this consideration biocomposites may often not be the appropriate choice due to their drawbacks in properties (Mahmud et al., 2021; Manu et al., 2022; see also Finding 2). Moreover, choosing biocomposites should be based on careful and holistic consideration of its sustainability benefits, taking also recycling into account, not just theoretically but practically (see 5.2 and Finding 9). Especially in product segments that are not recycled in the current context, such as most non-packaging applications and longer lasting plastic products, the study results indicate that biocomposites can be a feasible short-to-mid-term approach to increase sustainability of the material without really compromising recycling, as recycling is not done for fossil-based plastics either in those contexts. Even though the biocomposite approach could in some cases prevent some recycling, a holistic analysis of environmental effects could prove that the reduction of fossil-based content in the material can surpass the negative effect to sustainability from compromising recycling. Moreover, a holistic analysis of environmental effects should also consider how the environmental effects of the production processes of biocomposite materials compare to other alternatives (see Finding 3).

In the longer term, however, biocomposites may have more substantial blockers and the plastic industry actors should investigate other alternatives for increasing bio-based content. Generally, it is imperative for the plastic value chain to radically increase recycling and other circular economy practices in the long run for the plastic economy to ever reach sustainability (Ellen MacArthur Foundation, 2017; European Commission, 2018). These circular practices can minimize the need for virgin, but any material still required would need to be bio-based to completely decouple the plastic economy from fossil feedstock sources. In a world where recycling is done to a much greater extent, the results of this study indicate that biocomposites may not be a sustainable approach if they still cannot be recycled in the recycling system in place. Accordingly, in the long run the plastic industry should possibly investigate other ways of increasing bio-based content in plastics, such as by increasing the use of drop-in bio-based plastics (see Finding 4). However, the negative environmental implications of such bio-based plastics, namely their effects on food production, and increasing land and water use, remain mostly unsolved. These effects are likely dependent on how the plastic value chain succeeds in minimizing the overall need for virgin material by drastically increasing circular economy practices (Rosenboom et al., 2022). Biocomposites can still also have a role in some applications, and if the recycling system develops in a direction that also biocomposites can be recycled (see Finding 5).

Within developing and expanding recycling, this study identified that the current focus in plastic recycling on only packaging plastics is a major hurdle for increasing plastic recycling. Therefore, the plastic value chain could start by expanding recycling to also other segments of plastic use than packaging. Expanding outside packaging could unlock much higher recycling rates in general, but it could also support the development of recycling for biocomposite materials, which are more likely applied outside packaging (see Finding 2 and 5). Moreover, the plastic value chain could start to build recycling practices around small loop recycling. By arranging separate collection for various plastic products, plastic could be recycled to a much higher degree and with higher quality (Fredi & Dorigato, 2021; Lamberti et al., 2020). This could also support the development of biocomposite recycling since they would need to be recycled in a small loop (see Finding 5).

Although recycling is an important element in a circular economy of plastics, and the industry is seeing it as the most important factor, it seems that focusing only on improving recycling may result in a limited perspective in the efforts to increase sustainability. If considered in a systemic and holistic way, the sustainability of plastics can also be related to the inputs or outputs of the plastic economy system, as the open system modelling in this study has showcased (see 5.4). This study raises an important issue into question for the plastic industry that the goal should rather be an environmentally sustainable plastic economy, not just a circular plastic economy, and focusing only on the latter may sometimes be misaligned with the former. For instance, biocomposite materials can be more sustainable in some cases although they compromise recycling, because they can increase the bio-based input to the system (see Finding 9). From a systemic standpoint, the outputs of the system can also be a point where environmental sustainability can be positively contributed (e.g., Stegmann et al., 2022). However, the study indicates that the industry has not much considered alternative carbon products as an alternative fate for end-of-life plastic, which could prevent the carbon embedded in plastics from being released to the atmosphere. In this area, the industry could investigate more the possibilities of processing plastics into carbon products such as biochar, which could be a negative emission process in the case of bio-based waste plastics, and an element in the efforts to make the industry sustainable.

Finally, it seems from the findings that in the efforts of pursuing environmental sustainability, the negative climate effects of plastics dominate the environmental worries of the industry, as well as some of the issues of plastic littering and the accumulation of waste into nature. However, it seemed in the interviews that the industry is mostly neglecting an important problem, which is the issue of microplastic pollution. With plastic demand expected to rise in the future (Ellen MacArthur Foundation, 2017; Palm & Svensson Myrin, 2018), it is not likely that the problem will go away without the industry addressing it. Therefore, it is imperative that the industry also recognizes the magnitude of the microplastics issue and starts to find solutions for it (Ellen MacArthur Foundation, 2017; UN Environment Programme, 2023). Worryingly, it has been recently investigated that the recycling of plastics may also be a source of microplastics (Brown et al., 2023). Therefore, it seems important to make sure that different efforts to improve environmental sustainability by some means do not create negative implications elsewhere.

5.5.2 Implications to policymakers

In addition to the companies operating in the plastic industry and value chain, policymakers also have a role to play in facilitating the development of a sustainable plastic economy and the adoption of new sustainable materials. From the results of this study, some implications can be drawn for guiding policymakers in regulating the plastic industry.

Firstly, the study acknowledged some barriers in the value chain to adopting biocomposites. Small loop recycling practices are employed still to a rather limited degree, but they would be a critical element in being able to recycle biocomposites as well as in being able to recycle plastic waste in a high-quality way in general (Fredi & Dorigato, 2021; Lamberti et al., 2020; Plastics Europe, 2022b). Here policy actions could potentially provide support. In addition, it was identified as a clear barrier that the current plastic recycling is limited to packaging plastics (at least in the case context), and this boundary originates mostly from regulation and what kind of plastic products are part of producer responsibility (see Finding 4). This issue should be addressed by regulators to expand recycling requirements to also other plastic products, which could allow more plastic to be recycled and likely more biocomposite materials to also be available for secondary use in the longer term (see Finding 5).

Secondly, the study identifies a call for policymakers to recognize the potential benefits of long-term carbon storages more strongly in connection to the plastic economy (de Oliveira et al., 2021; Stegmann et al., 2022; Suh & Bardow, 2022). This study indicates that processing bio-based plastics to stable carbon products such as biochar is not yet considered in the industry. However, such approaches could have environmental significance. To support these alternatives ways of disposing plastic wastes, public initiatives could support investigations in alternative methods of disposing plastics that would prevent GHG emissions from being released to the atmosphere.

As an overarching problem in the plastic economy, one may identify the presence of negative externalities. Although plastic production and use create negative effects on the environment and societies in many ways, it seems that the plastic industry is not to any significant extent accountable for the harm that their production and products cause. Instead, society in general bears the long-term costs of the negative effects on the environment and human health, rather than following the polluter-pays principle. For the plastic industry actors in general, it is still too competitive to use environmentally harmful fossil sources in plastic production and follow a linear economic model rather than choose more sustainable materials and employ a circular economy. With various regulatory instruments, such as taxes or subsidies, policymakers could move accountability more towards the plastic industry, which could incentivize more sustainable options. In general, it seems that although there are many things that could be done to make the plastic economy more sustainable from a systemic standpoint, the economic incentives from the value chain actors to do so are mostly lacking. For instance, although processing plastics to long term carbon storage products may be systemically beneficial, there is little that companies can earn from this activity currently. Such situations could possibly be addressed with different policy instruments.

5.5.3 Theoretical implications

The results of this thesis study also offer some contributions to research literature. Firstly, the study contributes to research on plastic materials and, especially, the growing body of research on biocomposite materials as a sustainable material (e.g., Manu et al., 2022; Mohanty et al., 2018; Shanmugam et al., 2021). This study departs from the predominantly material technology-centric research that has characterized previous research on biocomposites (Shanmugam et al., 2021). Rather than being confined to a narrow examination of materials, this study has a broader scope that offers a practical perspective to the existing theoretical discourse on biocomposite materials, integrating viewpoints of the plastic value chain actors into the discussion. By employing a more holistic viewpoint into biocomposite materials, the study enriches the understanding of what implications these materials may practically have and how their implementation may be constrained.

Secondly, the study contributes to literature by integrating streams of literature that have not, to the author's knowledge, been integrated before. By integrating material technology research on bio-based plastics and biocomposites (e.g., Mohanty et al., 2018; Rosenboom et al., 2022), literature on circular economy in the plastic context (e.g., Ellen MacArthur Foundation, 2017), as well as scientific research on the sustainability transition of plastics (e.g., Stegmann et al., 2022; Suh & Bardow, 2022), the study unravels relationships and conflicts that may arise as new materials, in this case biocomposites, are adopted as sustainable alternatives to prevalent materials. In this way, the study increases understanding regarding improving sustainability and pursuing circular economy in the plastic context.

Thirdly, a theoretical advance made by this study is in the explorative approach taken. Generally, biocomposite materials have been limitedly investigated beyond predominantly material-technology centric scopes (Shanmugam et al., 2021). Therefore, instead of merely scrutinizing established phenomena, the study actively seeks to uncover and understand yet unexplored things related to the adoption of these materials. This forward-looking approach taken in the study contributes to the research community by laying groundwork for further research in the area.

Finally, the study makes a significant theoretical contribution through the modeling approach employed to understand the studied phenomena. The utilized open system model of the plastic economy depicts the industrial system as both a linear and a circular economy (see 3.2). This integration establishes a robust analytical framework to understand the practical industrial context and its effects on the environment. Thereby, it sets a precedent for future research in similar domains, thus also contributing to the evolution of theoretical frameworks that can capture environmental effects of industrial systems.

5.6 Limitations and future research

It is important to note that the results of this study are subject to some limitations. Firstly, since this is a thesis study, the study faces some limitations from the time and resources that were available to conduct the research. Due to constraints, the study was designed as a purely qualitative and explorative study. To provide more reliable research results, the study could have been complemented by some quantitative elements that would have allowed to measurably compare the sustainability of biocomposite materials with current alternatives in the practical plastic economy setting. However, conducting such a study would have required much more resources. Here, one can identify an avenue for future research to validate the findings made in this study with a quantitative approach.

Secondly, there may also be limitations in the study originating from the qualitative case-study approach taken. A clear threat to the generalizability of the results is the fact that the study was designed as a single case study, investigating only the Finnish plastic sector. Although the Finnish plastic sector was considered as a representative case, there may still be unique qualities of the Finnish context that negatively impact the generalizability of results. A wider approach, possibly as a multi-case study in several economies, could have delivered results that could be more reliably generalized to other countries, but such an approach would have required more resources. Perhaps future research endeavors may aim to validate the findings in other countries. Moreover, within the single case, the study managed to reach a sample of 19 interviews that covered well the different actors within the industry. For a thesis study, the number of conducted interviews may be considered good, but a more rigorous study would surely require a larger sample to accomplish more reliable results.

Thirdly, a limitation of the study may lie in overlooking some environmental effects of the examined material and processing alternatives. The study primarily focused on the circulation of carbon within the plastic economy system, but possibly failed to account for other meaningful domains outside only carbon. Lenses were mainly on the climate change effects of carbon dioxide in the atmosphere, which neglects, for instance, the effects that plastics may have on biodiversity or natural ecosystems through physical plastic waste or the chemicals that plastics may contain. One blind spot that remains in the industry is the effects of different material or process alternatives to the release of microplastics, which are generally identified as a growing concern (Ellen MacArthur Foundation, 2017). Future research studies could aim for more comprehensive analyses, which could entail expanding the investigation to a broader array of environmental domains beyond only carbon.

Even in the examination of carbon dynamics, the study may be limited in considering certain elements of the circulation carbon. One such domain is the source of energy, which e.g. Zheng & Suh (2019) and Stegmann et al. (2022) mention as a critical element in the sustainability of the industry. Many processes in the chemical and plastic industry require tremendous amounts of heat, including many recycling processes that rely on, for instance, melting plastic with heat in mechanical recycling or pyrolyzing plastic with heat in chemical recycling (Fredi & Dorigato, 2021). In generating such heat, fossil fuels are a usual suspect that such processes tend to rely on. Therefore, the energy consumption of different alternatives should possibly be more rigorously integrated into analyzing sustainability, to reveal the true sustainability impacts. Future research could aim to validate the results of this study with lenses on energy, as this study managed to integrate such a perspective only to a limited degree.

Another domain that this study may overlook relates to the discussion of bio-based materials. In this study, it was assumed that bio-based materials capture carbon into themselves and can constitute even a building block of a negative emission if the carbon is captured for the long term (de Oliveira et al., 2021; Stegmann et al., 2022; Suh & Bardow, 2022). However, the real impact may not be as straightforward, because extracting the material from some sources may have impacts on future carbon sequestration if the plants used for feedstock were instead left to grow and to capture even more carbon. Future research could examine these impacts with a more critical and detailed approach than this study managed to.

Fourthly, the study can be seen limited in how it considers the circular economy. Although the circular economy was investigated in broad terms in the literature review, its examination in the plastic context concentrated on recycling and energy recovery. This focus excludes other circular strategies which also provide appropriate approaches to address the negative impacts of the plastic economy to the environment. However, it might be argued that recycling is the most important area to be considered in this study, because recycling is sensitive to specific waste materials (Fredi & Dorigato, 2021), and biocomposite materials were seen to especially impact recycling. On the contrary, other circular strategies, such as reuse, repair, or reuse, deal more with how products are designed, used, or whether they are necessary at all, and less with what material products are made of. Nevertheless, the analysis conducted in this study could have considered what impacts biocomposite materials have in the possibilities of the plastic economy to employ also other circular strategies than recycling or energy recovery.

Finally, a broader limitation emerges from considering circular economy as analogous to sustainability. In literature, circular economy is rather considered as either a prerequisite or a possible way to achieve sustainability of the economy in general (Geissdoerfer et al., 2017). However, sometimes considering only the circular economy in sustainability efforts may be contradictory to genuine environmental impacts (Murray et al., 2017). Circular economy is also often criticized for being limited in questions regarding social sustainability, which on the other hand is very important in general considerations of the sustainability of the economy (Kirchherr et al., 2017; Murray et al., 2017). Because of this limitation, this study purposefully sought to examine only environmental sustainability as the lenses were strongly on the circular economy development in the plastic context. Nevertheless, a holistic study could have also taken other aspects of sustainability into account rather than only environmental as this study did. Such perspectives are left for further research in the area.

6 Conclusions

As the starting point for this study, biocomposites presented themselves as a potential innovative way to strengthen bio-based materials as serious competitors to fossil-based commodity plastics. Thus far, research on biocomposite materials has presented a gap between material technology-driven research related to what can be technically accomplished, and research on the practical needs, requirements, and conditions of the plastic value chain actors in adopting more sustainable materials. Aiming to close this gap, this thesis study focused on shedding light on the potential role of biocomposites in steering plastics towards sustainability. Through a qualitative and explorative single-case study, the study investigated the Finnish plastic sector, a representative case of a value chain that has experiences of biocomposite materials that various actors have brought to the market. Despite the limitations inherent in a qualitative case-study approach, the study has revealed valuable insights into what biocomposites may accomplish as part of the plastic industry's efforts for a more sustainable future.

Firstly, the findings of the research indicate that biocomposites may be a viable alternative material for increasing bio-based content, but only in a limited space of application areas. The most likely application areas were identified in replacing fossil-based plastic in non-packaging applications that are used for a longer time. If applicable in the product, biocomposite materials can utilize side-streams from different industries and valorize them for secondary use. This way, biocomposites can surpass some drawbacks that bio-based plastic feedstocks have related to their cannibalization of food production and increasing land and freshwater use. However, they do not demonstrate any significant advantages with regards to high prices or inferior properties that trouble many bio-based plastics. In addition, required changes in the production processes of biocomposites compared to other plastics impact their sustainability as a material.

Secondly, however, the recycling system for plastics proved to be a stumbling block for biocomposites. Although considered recyclable from a theoretical standpoint, the practical view from the interviewed industry actors was that biocomposites are very difficult to be recycled in the operational recycling system in place and rather end up rejected. Because of this hurdle, most value chain representatives were wary of considering the materials sustainable. However, operational changes in the recycling infrastructure could turn the situation around. Expanding recycling schemes to also other plastic segments than packaging would be beneficial to increase overall recycling rates of plastics, but also to allow biocomposite recycling processes to develop if recycling was done, in the first place, for waste segments were biocomposites are more likely to be present than in waste packaging plastics. Moreover, since it is critical for those operating recycling to know what specific material is in the waste plastic flows for the recycling to be done in high quality, small loop recycling processes could be more widely implemented to bring the overall quality of recycling up, as well as to accommodate the recycling of biocomposites.

Thirdly, there seems to be very limited changes in the patterns of final disposal of plastic materials as biocomposites are introduced. The results indicate that as biocomposites are likely not being recycled, they are likely to end up in waste disposal processes slightly more often than current fossil-based plastics, which seems like a negative factor for biocomposites. Moreover, the biodegradability of biocomposites, or plastics in general, was not considered as a good pathway due to the many problems associated with biodegradability. The study also considered possibilities for inserting carbon embedded in plastics to long-term carbon storages, but it was revealed that the industry does not, at least to any great extent, consider such opportunities at the point of final disposal. Although there are opportunities for creating even negative emissions by storing atmospheric carbon via bio-based plastics, these questions seem beyond specific material choices such as biocomposites, as value chain actors see little benefit in doing such activity for any plastics.

Nevertheless, despite the hurdles that the recycling system puts to adopting more biocomposite materials, they can still provide some sustainability benefits. Since recycling rates for plastics are generally still poor, and almost non-existent in many segments outside packaging applications, biocomposites can be a sustainable material choice in some application areas purely by substituting fossil-based material content. Thus, their adoption can be considered encourageable in the short-to-medium term, if the material is suitable to the application's function, and if the application is in an area where there is a low likelihood for the product to be recycled irrespective of the material choice. In the longer term, however, as recycling in the plastic value chain is expected to increase, there may be more benefit gained from bio-based material alternatives that are easier to be recycled in the operating environment.

In conclusion, biocomposites seem like an attractive approach for creating sustainable and bio-based materials, but there are many underlying mechanisms that impact the sustainability of the material. Although there are limitations in this conducted thesis study, the study still revealed mechanisms that affect the sustainability considerations of biocomposites. Thus, the study made contributions to an important discussion on the sustainability of materials. All in all, it seems that the plastic industry requires other major changes to seriously transition to a sustainable economy, but biocomposites can be an element within the overall transition. The approach is not a silver bullet, but it may be a start on the journey towards more sustainable material choices and ways of using materials.

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Appendix A: Interview guide used in the empirical data collection

Start of the interview: Data usage principles explained and recording permission asked.

Introduction of the research study and the agenda for the interview.

Informant background

- How would you describe in your own words the operations of the company or organization in the context of plastics and the value chain?
- What do you offer to your customers?
- What are you currently doing? What are your plans for the future?
- What does the circular economy of plastics mean to you and your company?

Description of the supply chain and circular economy of plastics (figure in Appendix 0 shown to the informant here)

- How does the presented overview of the plastic economy look? Is there anything essential missing from the high-level description?
- What kinds of actors are in the value chain?
- How do you perceive the different presented scenarios currently? What is their potential in the future in general? What challenges do you see?

Biocomposites in the plastic context, current state, and future

- How do biocomposites appear in today's plastic industry?
- What kinds of actors are involved?
- What are the key reasons for commercializing these materials?
- What are the key application areas?
- What are the key limitations for a wider adoption of biocomposites?
- From your perspective, what could be achieved in the plastic economy with increased use of biocomposites?

Biocomposites in different stages of the value chain

- What changes do biocomposites incur in the value chain? How? Why?
- How does the manufacturing or supply chain of biocomposites differ from that of fossil plastics or bio-based plastics?
- How would biocomposites fit into the "large loop" recycling system?

- How would biocomposites fit into the "small loop" recycling system?
- How would biocomposites be suitable for disposal based on biodegradation?
- How would biocomposites be suitable for capturing and storing carbon based on biochar production?
- What are the key limitations in different stages of the value chain and in different scenarios?
- What would be the ideal state regarding biocomposites in your opinion?

Who else could be interviewed for the research, value chain actors, or experts?

What would you still like to bring up that hasn’t been discussed yet?

What answers would you hope to receive from this research work?

Appendix B: Plastic economy framework used in the interviews