Summary

Plastic waste has come to the forefront of academic and political debates as a global problem that demands an urgent solution. Promoted by policymakers, academia, and corporations alike, the circular economy model presents a viable path to reach more sustainable levels of development. Likewise, emerging and disruptive technologies promise a profound socio-technical transformation that could enable the transition to a circular economy. However, their application in the plastic materials realm is not fully understood.

This thesis qualitatively explores the role, barriers, and impact of emerging technologies in the transition towards a circular economy in the plastic materials value chain. The research utilises two complementary methods to obtain a holistic understanding of the current state of affairs: a systematic literature review consisting of 55 academic articles and eight interviews performed to industry experts. Theoretical and practical insights are then jointly classified, analysed, and interpreted through the ReSOLVE and Multi-Level Perspective frameworks.

The analysis reveals that rather than individual technologies, four technologies enclosed in the chemical recycling, biorefineries, distributed economies, and Industry 4.0 concepts stand as major enablers of the transition towards circularity in the plastic materials space. Notwithstanding the profound systemic changes required, radical transformation is always likely to meet strong resistance. To overcome this friction, several adoption pathways are put forward and discussed in this research.

Technologies that feature the following characteristics will have the most prominent role in this transition:

- Low levels of risk
- High efficiency
- Showcasing of a company’s sustainability achievements
- Propelling a shift away from the mono-product focus
- Redefinition of the “waste” and “value” concepts
- The utilisation of the current waste management capabilities and waste streams
- Enabling of transparency and standardisation
- Conceptually understandable and mature enough for policy implementation
- Demonstrate a transformative impact
- Foster collaboration

LUND UNIVERSITY
School of Economics and Management

Master’s Programme in Innovation and Global Sustainable Development

Circular Economy in a Plastic World

How can emerging technologies enable the transition?

by

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Plastic waste has brought a severe pollution problem that demands immediate attention. Promoted by policymakers, academia, and corporations alike, the circular economy model presents a viable path to sustainable development. Likewise, the emergence of disruptive technologies promises a profound and imminent socio-technical transformation.

This thesis qualitatively explores the role, barriers, and impact of emerging technologies in the transition towards a circular economy in the plastic materials value chain through a systematic literature review and expert interviews. Theoretical and practical insights are jointly classified, analysed, and interpreted through the ReSOLVE and Multi-Level Perspective frameworks.

Technologies enclosed in the chemical recycling, biorefineries, distributed economies, and Industry 4.0 concepts are identified as major enablers of the transition towards circularity. Moreover, technologies that exhibit the least risk, demonstrate high efficiency, help showcase the company’s sustainability achievements, propel a shift away from the mono-product focus, utilise the current waste management capabilities, enable collaboration, and are conceptually understandable, will have the most prominent role in the transition.

Keywords: circular economy, emerging technologies, plastics value chain, sustainability transitions, systematic literature review, ReSOLVE framework, MLP framework.

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Alejandro Aristi Capetillo

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Table of Contents

List of Tables

List of Figures

1 Introduction

The section details the subject matter of this master thesis. It starts with a background presentation highlighting the importance of researching this topic. Then, it elaborates on the research problem related to the current state of affairs in the investigated subject. It continues with a description of the aim, scope, and research question, and concludes with a short outline of this document.

1.1 Background

There is no such thing as waste in nature. As a product of millions of years of evolution, the resultant output from any given natural cycle works as an input to a complementary natural process. Through this principle, the whole planet is interconnected, flawlessly working as a complex and adaptive system (Ostrom, 2009). The balanced nature of these interdependent and cooperative processes created the stable and predictable climate cycles upon which human civilisation emerged and thrived until now (Harari, 2015).

When looking at the current production and consumption systems, the linear model, also known as the 'Take-Make-Use-Discard' paradigm (McDonough & Braungart, 2002), adequately describes them. Although this model brought unprecedented economic prosperity in general terms, it is characterised as wasteful and environmentally unsustainable. Moreover, its myopic foundation, where the perceived value to the economic system is generated from producing and selling as many products as possible, positions it as the largest contributor to the risk of transgressing nature's delicate balance (Jørgensen & Pedersen, 2018).

The latest step in the evolution towards more encompassing and sustainable production and consumption systems is commonly referred to as the Circular Economy (CE). According to the Ellen MacArthur Foundation (EMF), a CE is defined as a "framework for an economy that is restorative and regenerative by design." (2017a). In short, the objectives of a CE are to design out waste and pollution, regenerate natural ecosystems, and extend product and material's life cycles for as long as possible (EMF, 2017b). This last objective is crucial in the transition towards a better relationship with the environment, especially concerning one of the most ubiquitous and still misused materials: plastic.

Due to its durability, malleability, and tuneable properties, it is hard to find a product or industry with no close ties with plastic materials (Hsu, Domenech & McDowall, 2021). However, the mismanagement of this material has brought severe pollution problems on a global scale. Plastic has intruded into each of the Earth's life-supporting cycles and organisms that inhabit this planet – from the Arctic ice sheet (Bergmann et al., 2019) to human placentas (Ragusa et al., 2021). Not to mention that, when measured by total mass, plastic materials will weigh more than fish in the oceans by the year 2050 (WEF, 2016). Addressing this issue is therefore of utmost importance to ensure the present and future stability of the planet's ecosystems.

Emerging technologies, framed under a CE model, offer a promising path to tackle this issue and enable a thriving society for decades to come. Nonetheless, due to these technologies' novelty, the shape and scope of this route is still unclear and therefore, it deserves a closer look.

1.2 Research Problem

Several attempts to understand the relationship between the usage of innovative technologies for sustainability purposes in the productive side of economies have been put forward in the research sphere. Pagoropoulos, Pigosso & McAloone (2017), Vrchota et al. (2020), Zeiss et al. (2021), and Acioli, Scavarda & Reis (2021) employ a systematic literature review methodology and point their attention to the role that digital technologies, through the umbrella term of 'Industry 4.0', have in the implementation of CE practices. However, they do not focus on the dynamics of the plastic materials value chain while also failing to account for the impact of non-digital technologies on this domain.

Other papers (Birtchnell & Urry, 2013; Gligoric et al., 2019; Kouhizadeh, Zhu & Sarkis, 2020) discuss the function of specific emerging technologies (3D Printing, Internet of Things, and Blockchain) as enablers of a CE in the manufacturing stages of products but fail to explore the interconnection with other technologies and thus, are unable to comprehend the impact from a systemic viewpoint.

Further on, research gaps detected by Bag et al. (2018), Nižetić et al. (2019), Ranta, Aarikka-Stenroos & Väisänen (2021) highlight the need to investigate precisely how innovative technologies (Industry 4.0) lead to supply chain sustainability, how to apply the CE concept on the plastic waste and recycling grounds, as well as the necessity to reduce the knowledge gap through empirical instead of solely theoretical research, respectively.

From a theoretical perspective, the study of this phenomenon through a sustainability transition lens has also received attention from the research community (Farla et al., 2012; Gardner et al., 2019; Markard, Raven & Truffer, 2012; Papachristos, 2019; Strøm-Andersen, 2019). However, existing research fails to analyse the topic considering the three main concepts of the current thesis: circular economy, emerging technologies, and the plastic value chain.

1.3 Aim, Scope, and Research Questions

Based on the foregoing, one can assume that understanding the emerging technologies' interconnection and alignment with the CE principles in the plastic materials sphere is a knowledge area that has not yet been thoroughly researched. Hence, the aim of this thesis is to identify and understand, from the theoretical and practical perspectives, how emerging technologies enable the transition towards a CE model. Moreover, it is of interest in this research to discover the barriers that these technologies encounter as well as the impact they exert on the phenomenon in question.

Through a systematic literature review method complemented by a set of expert interviews, the scope of this thesis is bound to the manufacturing steps of the plastic materials value chain. Therefore, pursuing an exploratory approach, this analysis is guided by the following research question:

How can emerging technologies enable the transition towards a circular economy model along the manufacturing stages of the plastic materials value chain?

This study strives to contribute to theory-building on sustainability transitions, emerging technologies, and supply chain sustainability knowledge domains by providing insights and observations related to the entangled and extensive plastic realm.

The results of this thesis might be of interest to practitioners in the innovation, supply chain, or sustainability areas of companies who are part of the plastic materials value chain and seek to implement CE principles through the use of innovative technologies. Likewise, policy-makers might also be interested in this thesis' output when aiming to have a deeper understanding of how technology can enable circularity at the firm, regional, and national levels.

1.4 Thesis Outline

The rest of this writing is organised as follows. Section 2 puts forward a frame of reference for the main topics discussed in this thesis. The methodologies and data are detailed in Section 3, followed by the descriptive and thematic analysis of the results in Section 4. In Section 5, a discussion of these results within the selected sustainability transitions framework and further directions of the investigation are presented. Lastly, in Section 6, the thesis' concluding remarks are detailed.

2 Frame of Reference

This section gives a brief background to the main concepts used in this thesis: Circular Economy and its operationalisation framework, the plastic value chain and its manufacturing stages, the definition of emerging technologies, and the Multi-Level Perspective framework as part of the sustainability transitions theory.

2.1 Circular Economy and the ReSOLVE Framework

With roots in several disciplines such as environmental economics, industrial ecology, and corporate sustainability (e.g. Field, 1994; McDonough & Braungart, 2002), the concept of CE is presently being promoted by policymakers, academia, and corporations as a viable path to enable sustainable ways of development (Geissdoerfer et al., 2017) and accomplish the Sustainable Development Goals put forward by the United Nations (2021).

From an academic perspective, a CE can be defined as:

> *"an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."*
>
> *(Kirchherr, Reike & Hekkert, 2017, p.224-225).*

In the CE model, economic value is created by focusing on preserving the intrinsic value of products, and it recognises the importance of the economy in the current system of production and consumption by fostering efficiency at all scales (EMF, 2015). Most importantly, the authors state that the goal of a CE is to not only lessen the harm associated with the linear economy but rather create a positive and reinforcing development cycle to sustain life in the long term. Figure 1 exhibits the continuous flow of technical and biological materials or the production and consumption of goods and services in a CE.

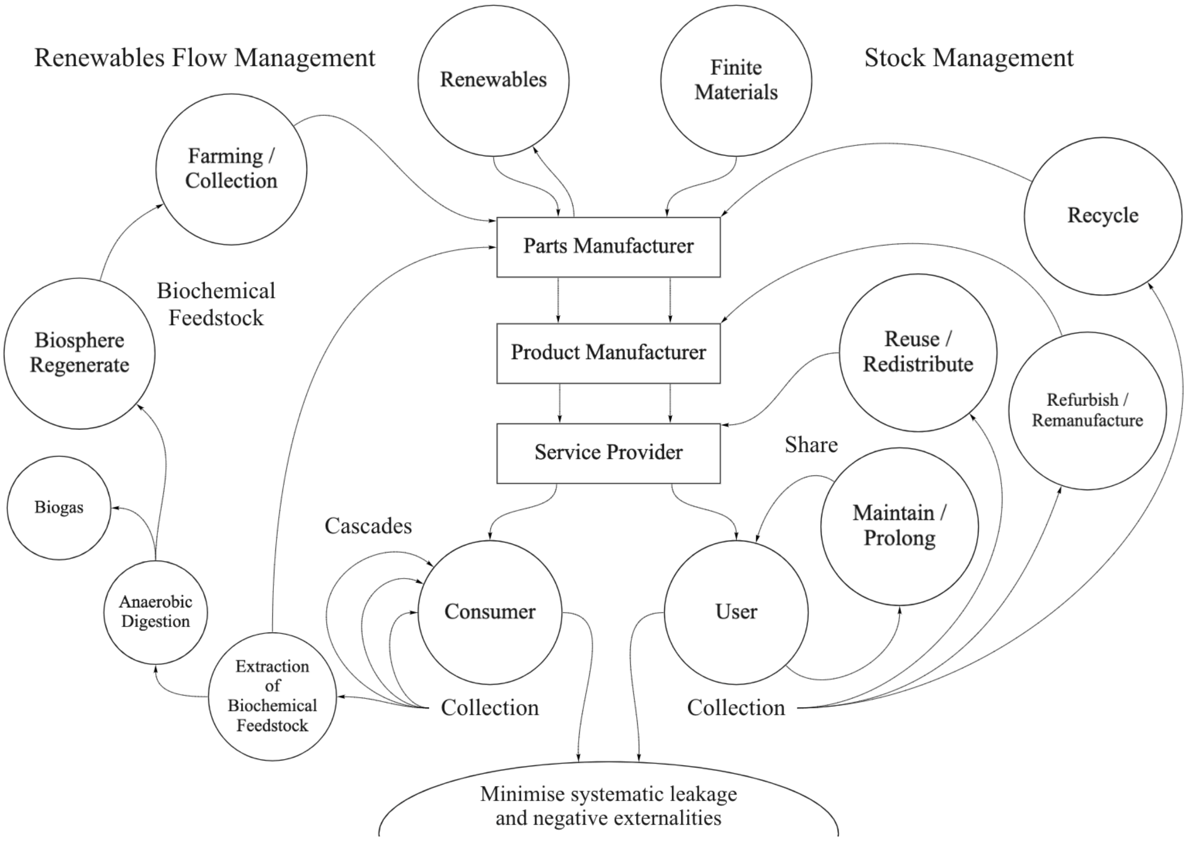


Figure 1. Circular Economy Systems Diagram.
Own diagram based on Ellen MacArthur Foundation (2019).

The CE ideology reflects on three fundamental principles (EMF, 2015, p.22):

1. Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
2. Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles
3. Foster system effectiveness by revealing and designing out negative externalities

In turn, these principles can be operationalised into six action areas that constitute the ReSOLVE framework (EMF, 2015): Regenerate, Share, Optimise, Loop, Virtualise, and Exchange. Each of these action areas represents a business opportunity that, together with technological tools, habilitates companies and governments to create solutions and regulations that foster the shift towards a CE (EMF, 2015). In this thesis, the ReSOLVE framework is used to analyse and interpret the investigation results in relation to the CE principles. More information about each action area is given in Section 4.

2.2 The Plastics Value Chain

The term ‘plastics’ encompasses a varied and ever-expanding range of polymers used on products from several industries such as automotive, construction, packaging, electronics, and many more. Table 1 showcases a summary of the main types of polymers produced nowadays.

Table 1. Primary Plastic Production by Polymer Type.
Own table based on Geyer, Jambeck & Law (2017) and Wu & Montalvo (2021).

Polymer Type	**Applications**
Polypropylene (PP)	Wrapping, caps, potato chip bags, packing tape
Low-density polyethylene (LDPE)	Shopping bags, general packaging material
Polyester, polyamide & acrylic (PP&A)	Textiles (clothing, furniture), carpets
High-density polyethylene (HDPE)	All types of bottles (shampoo, milk, motor oil)
Polyvinyl chloride (PVC)	Plumbing pipes and fitting, blister packaging
Polyethylene terephthalate (PET)	Single-use drink bottles
Polyurethanes (PU)	Mattresses, shoes, cars, thermal insulation
Polystyrene (PS)	Disposable plates and cups, food containers

The plastic value chain is complex and touches upon several business sectors along its way. Nielsen & Bauer (2019) detail the process as follows. From a linear economy perspective, the majority of plastics are produced from light hydrocarbons such as crude oil, which is then converted to naphtha or a natural gas liquid like propane or ethane. These raw materials are then *cracked* to produce monomers like propylene or ethylene that are subsequently *polymerised,* resulting in materials like polypropylene (PP) or polyethylene (PE). These last two steps are carried on by the monomer producers (also known as ‘crackers’) and the polymer producers, respectively.

Then, Nielsen and Bauer (2019) explain, the virgin polymers, which commonly come in the shape of granulates or ‘flakes’, are mixed with additional additives to obtain the desired properties for the intended application. Further on, the companies known as ‘converters’, transform this plastic mix into products through processes like moulding, blowing or extrusion. The resultant items are then handed into the brands to be sold to the end consumers, or they are used as components in more elaborate products.

After these final products are consumed or used, they are collected and sorted by waste management firms, who then pass the recyclable waste to the ‘recyclers’ or send the non-recyclable share to be either incinerated or buried in a landfill (Nielsen & Bauer, 2019). The recyclable portion is then processed to be used again, re-starting at the polymer or conversion stages. Figure 2 provides a graphic explanation of this process.

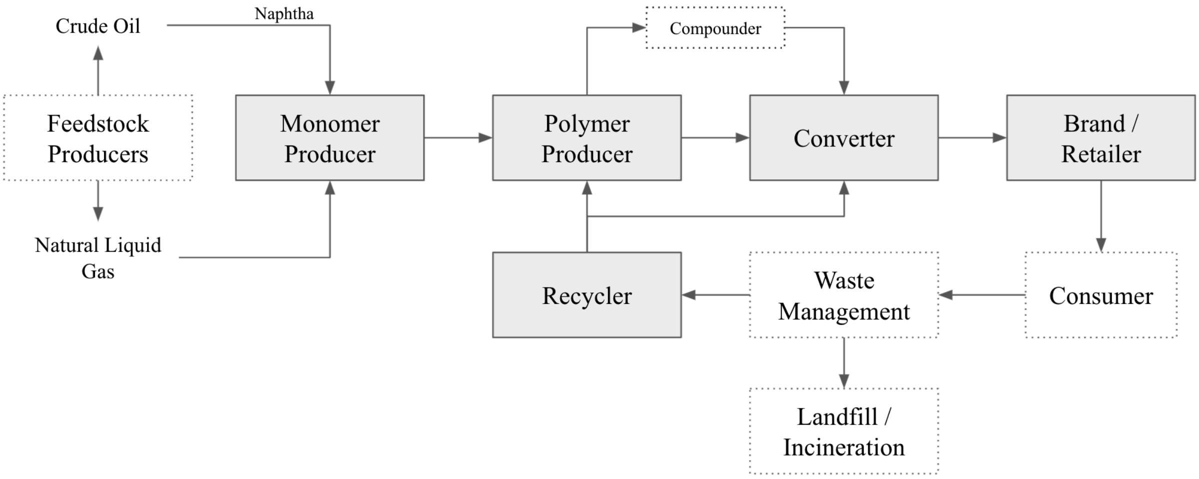


Figure 2. Plastic Materials Value Chain.
Key: grey boxes represent this thesis' considered stages.
Own diagram based on Nielsen & Bauer (2019) and UNPRI (2019).

When reviewing the shape and size of the value chain's main actors, the largest share in terms of the number of companies and overall turnover is taken by the compounders and converters, represented mainly by small and medium businesses (EuPC, 2017). Next, due to a necessity of developing economies of scale to achieve profitability, the production of monomers and polymers is dominated by global petrochemical companies with close ties to the oil and energy sectors such as Dow Chemical, Exxon Mobil, LyondellBasell, Sabic, among others (Nielsen & Bauer, 2019; UNPRI, 2019); however, significant players that specialise in the polymerisation stage also achieve a considerable market share (e.g. Covestro, Borealis). Lastly, the recycling stage is depicted by having the fewest players and turnover share (EuPC, 2017). Table 2 showcases key figures from the European Plastic Industry. Although these statistics describe the situation in Europe, these proportions and magnitudes are also applicable at the global level.

Table 2. Number of Companies and Turnover in the European Plastic Industry.
Own table based on Nielsen & Bauer (2019). Data from EuPC (2017).

	Companies		**Turnover**		**Type of companies**
Monomer and Polymer Producers	2,000	3.8%	€100 Billion	27.6%	Large multinationals
Compounders and Converters	50,000	94.3%	€260 Billion	71.8%	Small and medium sized businesses
Recyclers	1,000	1.9%	€2 Billion	0.5%	Mostly large and medium sized companies
Total	53,000	100%	€362 Billion	100%	

2.3 Emerging Technologies

Most likely because of their transformative potential and underlying sophistication, the study of 'emerging technologies' has attracted the attention of researchers in recent years. This has caused an increasing number of related articles, and thus, several definitions of this term have been put forward. For this thesis, the definition by Rotolo, Hicks & Martin (2015) is used and it entails the following attributes.

First, they are fundamentally different from what has previously been utilised to attain a similar goal, and so, they exhibit a *radical novelty* (p.20). Second, compared to other non-emerging technologies, they achieve a *relatively fast growth* (p.23) rate. Third, emerging technologies display *coherence* (p.25) and persistence in terms of definition and scope. This may be expressed by, for example, a reduction in the number of terms used by scientists to define a specific technology. Fourth, they exercise a *prominent impact* (p.27) on either a specific domain or a broader area within the socio-economic system by changing the constitution of actors, institutions or the interaction between them. Fifth, they are surrounded by *uncertainty and ambiguity* (p.29) regarding their potential outcomes and applications, which could also result in undesirable or unintended consequences. Table 3 displays some examples of currently emerging technologies applicable to the plastics value chain.

Table 3. Examples of Emerging Technologies.
Table adapted from Esmaeilian et al. (2020, p.2). Descriptions based on Bag et al. (2018).

Technology	**Description**
Artificial Intelligence (AI)	Simulating human intellect using computer systems.
3D Printing / Additive Manufacturing	The process of creating items using computer control by layering materials together.
Internet of Things (IoT)	Using the internet to connect and monitor industrial equipment and physical devices.
Blockchain	A public digital ledger with a decentralised, distributed data structure.
Chemical Recycling	A range of technologies used to recycle plastic and bring it to a monomer state.
Biorefineries	A refinery that, instead of petroleum, uses bio-based feedstock to produce chemicals, plastics, and others.
Big Data Analytics	Usage of advanced analytic methods in large, complex, and diverse types of data sets.

Lastly, for simplicity's sake and acknowledging that their respective definitions and scope are not equal, other terms that refer to a similar conceptual definition, such as Industry 4.0 (Sung, 2018), Transformative Technologies (TT) (Clark, Trimingham & Storer, 2019), or Key Enabling Technologies (KET) (European Commission, 2009) are included in the 'emerging technologies' concept of this thesis.

2.4 Sustainability Transitions and the MLP Framework

Within the sustainability transitions studies, the Multi-Level Perspective (MLP) framework (Geels, 2002) is a tool to analyse and "understand the complex dynamics of sociotechnical change." (p.1259). It has shown remarkable acceptance in the academic field for its broad applicability in the study of technological transitions through a systemic and nested approach. For this reason, it is the framework used in the 'Discussion' section.

The MLP is built upon the concepts of 'technological regimes' and 'technological trajectories' put forward by Nelson & Winter (1982) and further enhanced by Rip & Kemp (1998). Through these constructs, the authors propose that a system's inherent stability is produced as an outcome of the 'co-ordination' between the organisations and routines that are part of it. Expanding on this definition, a regime is composed of its actors and the activities they perform. When conducted on a recurrent basis, these activities and their performance style become embedded in the organisation's culture. This routine-based performance defines, amongst other things, the innovation-search paradigm to be utilised at the firm level. When sufficient organisations within a technological regime share a similar innovation-search path, salient technological trajectories emerge. Therefore, the stakeholders of a technological regime conjunctively achieve systemic stability by establishing the direction of innovative activities. Furthermore, the regime's position, shape, and magnitude are incrementally solidified with each step taken through a particular technological trajectory.

The activities and actors considered in the regimes' approach englobe not only engineers or individuals in the innovation-seeking journey. They also include several other stakeholders (e.g. users, policymakers, suppliers, scientists, banks, etc.) and knowledge areas (e.g. manufacturing processes, product characteristics, corporate governance structures, etc.) that contribute to the generation of the routines mentioned above (Rip & Kemp, 1998). This means that the technological regimes and trajectories are also bound to a set of rules and social structures. Thus, Geels (2002) employs the term 'socio-technical regimes' (S-TR) in reference to the configuration of actors and activities within a determined social context. The author outlines the seven dimensions that constitute a S-TR: technology, user practices and markets, culture, infrastructure, industry structure, policy, and techno-scientific knowledge.

S-TRs, according to Geels (2002), while slowly and incrementally changing, are essentially constrained by pressures from two sides. First, the socio-technical landscape, consisting of the external and heterogeneous forces and trends that fall outside the regime's boundaries and control territory. For example, these are broader cultural values, demographic trends, or for this thesis' purpose, environmental issues. An important attribute of the socio-technical landscape is that it changes at an even slower pace than the S-TR.

As the second S-TR-constraining pressure, the technological niches or niche innovations bring disruptive and agile change to the regime's structure. Since these niches are generated outside the S-TR's ambit, they are intrinsically 'shielded' against the standard adversities that the other innovations located within the S-TR undergo. Niche innovations are also indirectly influenced by the socio-technical landscape pressures since they are still part of the broader system. However, rather than merely being constrained by them, these pressures may act as catalysers, paving their way to challenge the S-TR's dynamics. This translates into the construction of novelties with immense potential to fundamentally redefine the S-TR's status quo. Ultimately, if a niche manages to establish itself and modify the S-TR, it may also end up changing the socio-technical landscape orientation. Examples of niche innovations mentioned by Geels (2002) include army-funded tools like digital computers, radars, and jet engines. Figure 3 offers a graphic description of the MLP.

Based on the foregoing, the MLP can be understood as a representation of the connection, influence, and interaction between the three elements of a technological transition – regime, landscape, and niche innovations.

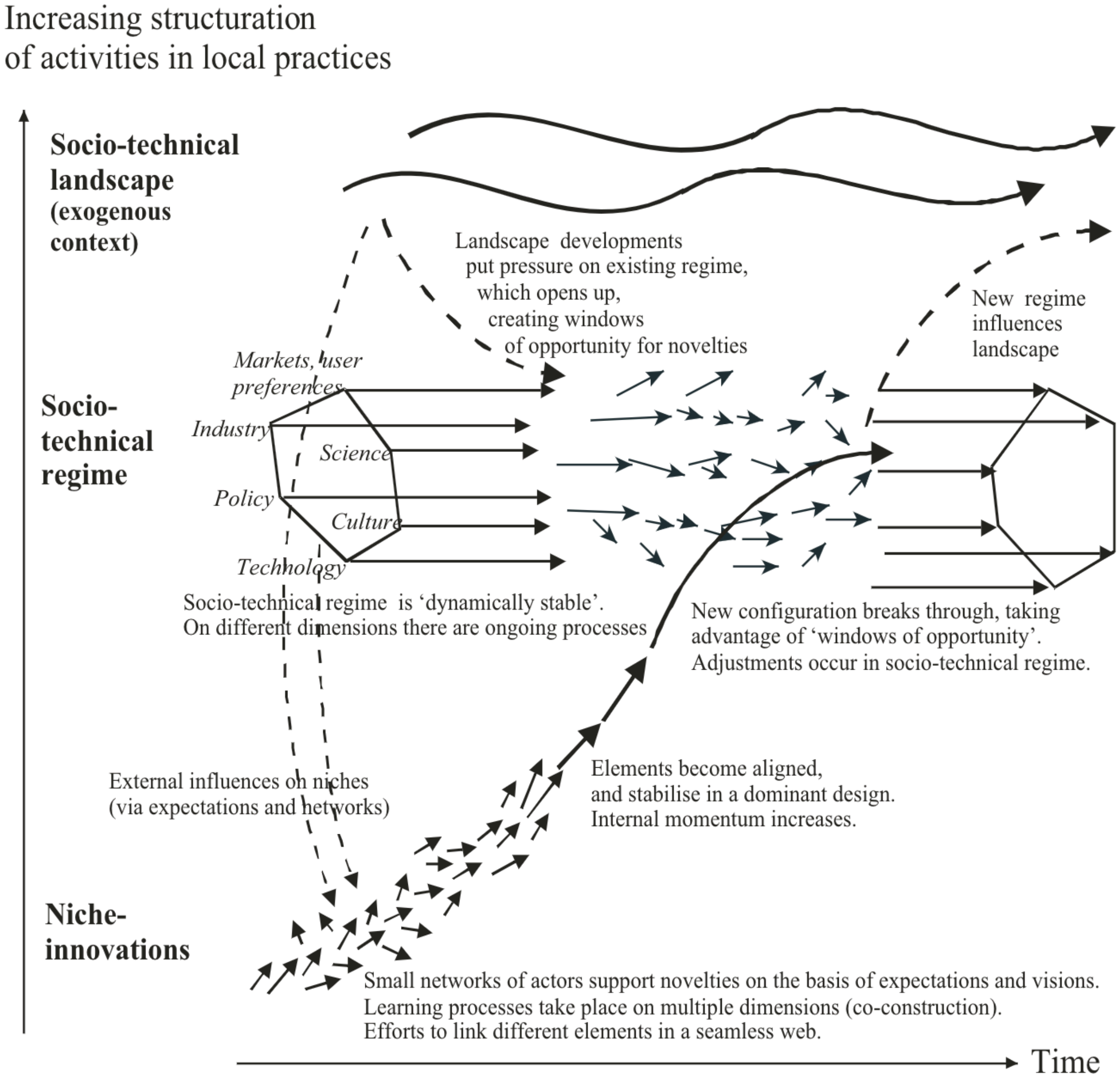


Figure 3. Multi-Level Perspective on Technological Transitions.
Diagram from Geels (2011, Fig. 2).

3 Methodology

This section starts with a description of the general research strategy applied in this thesis. It then continues with a detailed explanation of the methods and data used in both the systematic literature review and expert interviews. It concludes by elaborating on the limitations that arise from the chosen methodology.

3.1 Research Strategy

Qualitative approaches are widely utilised when researching new phenomena in nascent knowledge domains (Ritchie et al., 2013). Considering the relative novelty of the *circular economy* and *sustainability transitions* concepts, as well as the inherently innovative aspect of the *emerging technologies* field, an exploratory approach is utilised in the present research. For this, the employed research strategy follows a qualitative approach and consists of a systematic review that is complemented by expert interviews (Figure 4).

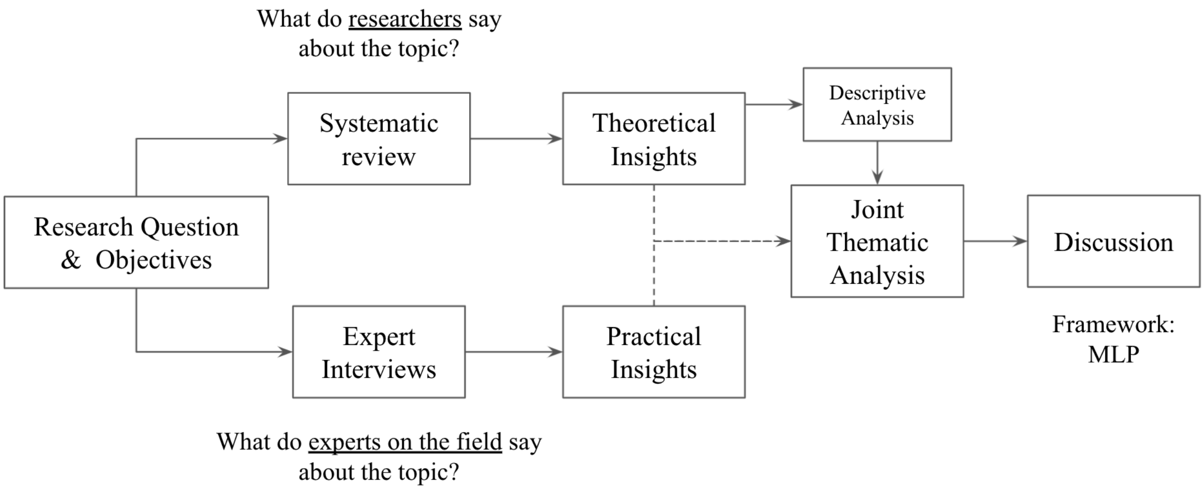
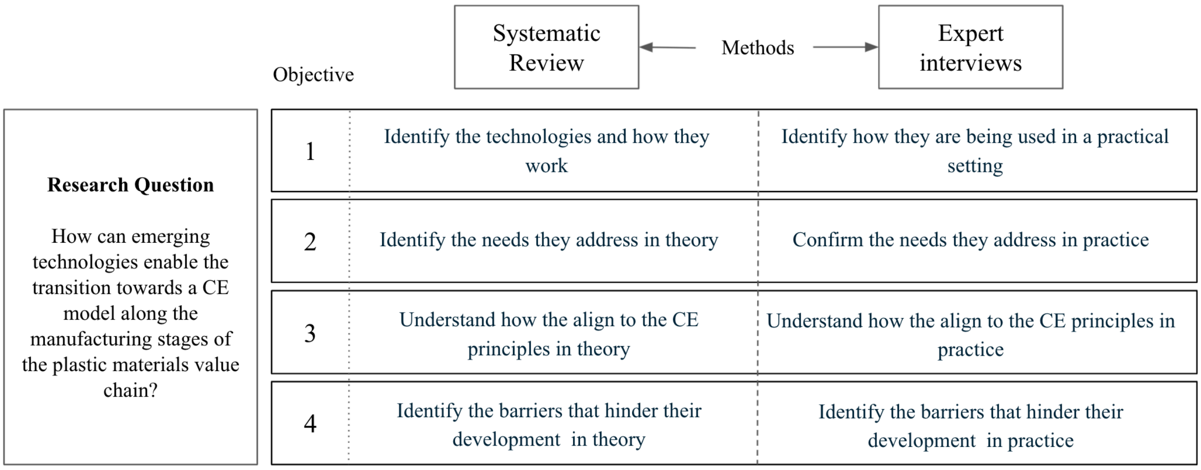


Figure 4. Research Strategy.

The intention behind conducting two separate albeit supplementary methods is to get a comprehensive understanding of the phenomenon in question. This is the logic behind the concept of *triangulation* as described by Olsen (2004) and Denscombe (2017, p.154). Figure 5 displays the objectives of each research method employed concerning the research question presented in Section 1.



Research Question

How can emerging technologies enable the transition towards a CE model along the manufacturing stages of the plastic materials value chain?

Objective	Systematic Review	Expert interviews
1	Identify the technologies and how they work	Identify how they are being used in a practical setting
2	Identify the needs they address in theory	Confirm the needs they address in practice
3	Understand how the align to the CE principles in theory	Understand how the align to the CE principles in practice
4	Identify the barriers that hinder their development in theory	Identify the barriers that hinder their development in practice

Figure 5. Research Methods and Objectives.

Alternatively, this thesis' research process follows two different branches of knowledge understanding when seen from an epistemological point of view. On the one hand, the systematic literature review falls under and aims to fulfil a *positivist* perspective. That is one that relies solely on empirical, objective, and scientific evidence (Armstrong, 2013, p.29). On the other hand, the interviews with on-field experts who contribute to shaping the industry dynamics provide an understanding from an *interpretative* perspective that rests on a subjective time- and context-dependent basis (Biggam, 2014, p.168). Thus, by combining both standpoints, the results are expected to showcase a clearer picture of the emerging technologies' role in transitioning towards a CE model in the plastics value chain.

Furthermore, the qualitative methods bring value to the research process through an inherently broad potential for the development of new concepts (Gioia, Corley & Hamilton, 2013). According to Bell, Bryman & Harley (2018, p.23), through the analysis of observations and findings, the employment of inductive techniques generates inferences that could be applicable at the general level. However, the authors' state, "[J]ust as deduction often entails an element of induction, the inductive process is likely to involve some deduction." (p.23). This is reflected in this thesis' research strategy through the employment of the two methods mentioned above.

Whereas the systematic review aims to understand the academic perspective from a primarily inductive stance, the analysed papers are based on previous researchers' work and therefore relate to a deductive approach. Correspondingly, a similar phenomenon can be seen through the expert interviews where, although they are primarily following an inductive strategy, the questions that shape the conversation exhibit a relationship to the systematic literature review, also showcasing a deductive approach. Hence, through an iteration and synthesis of these two approaches is how this thesis aims to expand existing research and understand the phenomenon or *puzzle* in question – an approach also called abductive reasoning (Bell, Bryman & Harley, 2018, p.24). Figure 6 exemplifies this logic.

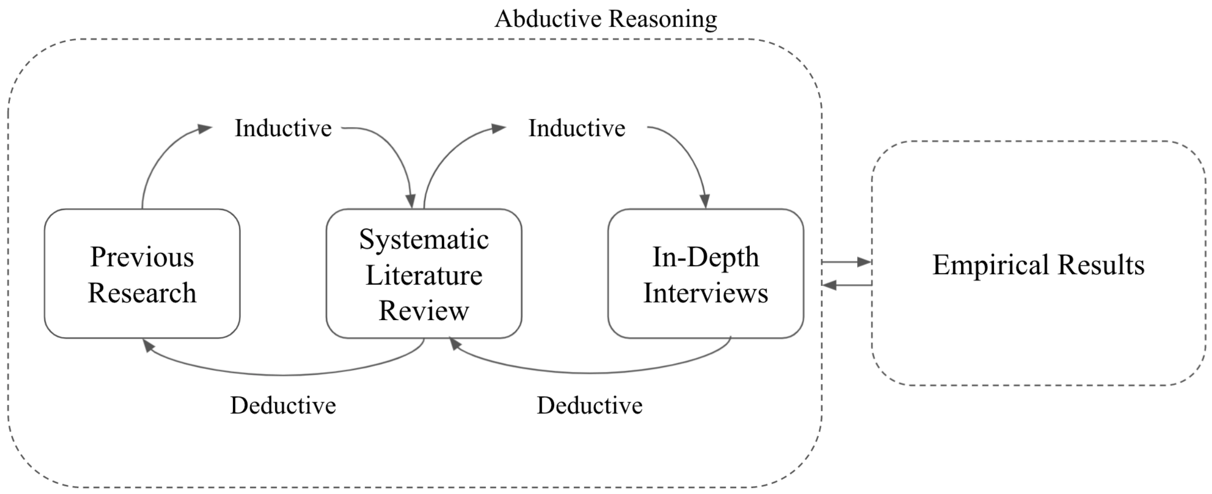


Figure 6. Research Approach.

In the following subsections, a detailed description of each method is put forward.

3.2 Systematic Literature Review

Following the approach taken by several related papers on the topic (see Table 4), this thesis employs a systematic review methodology put forward by Tranfield, Denyer & Smart (2003) with the aim of "synthesizing research in a systematic, transparent, and reproducible manner" (p.207). The central idea of using this research methodology is to apply a specific set of principles used in the medical sciences' investigation into the management sphere (Tranfield, Denyer & Smart, 2003). The main objective of using this research methodology, the authors' state, is to counteract the paper selection bias by making transparent the assumptions and values behind a literature review.

This thesis focuses on the search, identification, appraisal, and synthesising of studies that combine three main concepts within the plastic materials value chain: emerging technologies, circular economy, and sustainability transitions.

Table 4. Related Systematic Review Studies.

Reference	Data Sources	Main Theme
Pagoropoulos, Pigosso & McAloone (2017)	Scopus and Web of Science	The emergent role of digital technologies in the Circular Economy
Bag et al. (2018)	Scopus	Identify the Industry 4.0 enablers of supply chain sustainability
Vrchota et al. (2020)	Scopus and Web of Science	Sustainability outcomes of green processes in relation to Industry 4.0 in manufacturing
Acioli, Scavarda & Reis (2021)*	Emerald Insight, Scopus, and Web of Science	Applying Industry 4.0 technologies in the COVID-19 sustainable chains

* Although this reference does not follow a systematic review method, its strategy and objectives follow a similar logic.

Important to mention is that even though the papers detailed in Table 4 showcase similarities in regards to the systematic review method and overall theme, they only partially overlap with the current thesis approach since the lens (Multi-Level Perspective), data sources (additional journals included), industry focus (plastics), and analysis procedure (systematic review thematic analysis complemented with expert interviews) are fundamentally different.

With reference to the process used in the study by Bag et al. (2018, based on Tranfield, Denyer & Smart, 2003), the systematic review presented in this thesis consists of three procedural stages showcased below (Tranfield, Denyer & Smart, 2003):

1. Planning the review

2. Conducting the review

3. Reporting the review

The following subsections detail the performed activities and phases for each stage of the present investigation.

3.2.1 Planning the Review

Phase 0

The initial phase, 'Phase 0', relates to the identification of the need for a systematic review (Tranfield, Denyer & Smart, 2003). From the initial scoping where the studies from Table 4 were found, it became apparent that very few investigations that relate to the topics in question had been published and that these articles fail to focus on the specific perspective that is being researched in this thesis.

Phase 1

Onwards, 'Phase 1' relates to the preparation of a proposal for the review (Tranfield, Denyer & Smart, 2003), which signifies the definition of research questions and objectives. For this thesis, the objectives and research question used for the systematic review mimic the ones of the whole thesis and are summarised here:

RQ: How can emerging technologies enable the transition towards a CE model along the manufacturing stages of the plastic materials value chain?

Systematic Review Objectives: From the theoretical standpoint, identify the technologies and how they work, identify the needs they address, understand how they align to the CE principles, and identify the barriers that hinder their development.

Phase 2

Further on, 'Phase 2' involves the design of a review protocol (Tranfield, Denyer & Smart, 2003) which includes the specific questions addressed, the sample, search strategy, and inclusion and exclusion criteria of studies for the review (p.215). The inclusion criteria are detailed in Table 5, while the complete review protocol can be found in Appendix A.

Table 5. Inclusion Criteria.

Inclusion criteria	**Motivation**
Is the article published in a peer-reviewed scientific journal?	This criterion guarantees a certain level of quality in the reviewed publications.
Is the publication written in English?	Research written in English is easier to understand and assess by the reviewer.
Does the publication treat the interaction or exhibits a direct connection between emerging technologies, circular economy, and the plastics industry?	The publication must adhere to the thesis' central theme.

3.2.2 Conducting the Review

Phase 3

This step begins with 'Phase 3', which relates to the identification of research (Tranfield, Denyer & Smart, 2003). For this, two approaches put forward by Rowley & Hartley (2008) are taken. For the initial scoping performed on April 3rd, 2021, a 'briefsearch' strategy is used (p.115). Further on, the 'building blocks' strategy is used for the construction and refinement of search queries through the use of boolean functions such as "AND" or "OR" (p.115). Table 6 showcases the keyword clouds used for the search process in the different databases.

Table 6. Keywords Clouds for the Search Process.

Topic	Sustainability Transitions	Circular Economy	Plastic Value Chain		Emerging Technologies
Subtopic	-	-	Value chain	Plastic	-
Keywords	sustainability, sustainability transition*, transition*, sustainable, sustainable transition*, MLP, multi level perspective, regime*, socio-technical	circular economy, circular, circularity	supply chain*, value chain*, manufacturing, manufacturing chain*	plastic*, polymer*, monomer*, recycler*, plastic converter*	digital technolog*, emerging technolog*, disruptive technolog*

The final search queries for each database can be found in Appendix B. These strings can be re-run by simply copying and pasting the search syntax under the advanced search options of the corresponding database websites. However, the searches were performed on April 16th, 2021, so the results might differ considering the constant updating of the knowledge space.

The databases are selected based on the reference papers showcased in Table 4, adding two other relevant publishers to the mix: Wiley and EBSCOHost. In total, five databases are scanned for the systematic review of this thesis: EBSCOHost, Emerald Insight, Scopus, Web of Science, and Wiley. This comprises a comprehensive, high-quality, and cross-disciplinary review of published articles as defined by Tranfield, Denyer & Smart (2003).

Phase 4

Within this phase, a selection of studies is carried out (Tranfield, Denyer & Smart, 2003), and it involves several activities. For this thesis, the digital platform 'Covidence' is used to facilitate the process. The activities performed are as follows: import of references to the platform, removal of duplicates, screening against title and abstract, full-text assessment, and based on other systematic reviews (Klewitz & Hansen, 2014; Pagoropoulos, Pigosso & McAloone, 2017), an additional step of including relevant cited papers (also referred to as 'snowballing') is also taken. Based on Moher et al.'s (2009) paper, the diagram presented in subsection 4.1.1, follows a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) scheme, which exhibits the process and outcomes of each activity.

Phase 5

During 'Phase 5', an assessment of the studies' quality is carried out (Tranfield, Denyer & Smart, 2003). Through a determined set of questions put forward by Popay, Rogers & Williams (1998), the researcher can objectively evaluate the studied writings, especially when they follow a qualitative and hence, more complicated approach (Tranfield, Denyer & Smart, 2003). Although this phase usually does not affect the included or excluded studies, it helps the researcher to judge the individual contribution of each included writing in the next phase of the systematic review ('Phase 6') (Booth, Sutton & Papaioannou, 2016). Table 7 describes the questions proposed by Popay, Rogers & Williams (1998) that are applied in this thesis.

Table 7. Qualitative Studies Evaluation Criteria.
Adapted from Popay, Rogers & Williams (1998).

Criteria	Key Question
Responsiveness and flexibility	Is the study design appropriate for the real-world situations encountered?
Context sensitive	Has the research been developed in such a manner that it can adapt to changes that occur throughout the study?
Sampling strategy	Is the used sample satisfactory to generate knowledge?
Data quality	Are the different sources of knowledge being explored or compared?
Theoretical adequacy	Do the researchers showcase the process by which they interpret the data in a transparent manner?
Generalisability	Is there enough evidence to back up claims of generalisability?

Phase 6

'Phase 6' of the systematic review consists of extracting the data from the included studies (Tranfield, Denyer & Smart, 2003). It involves the creation of a data-extraction form which, according to Tranfield, Denyer & Smart (2003), should serve three purposes: to evaluate the included studies, to act as a historical record of the decisions taken, and to act as a data-repository from where the analysis will emerge. The data-extraction form designed and utilised for this thesis can be found in Appendix C.

As Tranfield, Denyer & Smart (2003) comment, it is helpful to involve two or more independent researchers in this phase; however, the only author carried out this step by himself for this thesis.

Phase 7

The last phase of this stage, 'Phase 7', consists of the analysis and synthesis of the compiled information from the systematic review (Tranfield, Denyer & Smart, 2003). Following the example of Kouhizadeh, Zhu & Sarkis (2020) and Ramirez-Peña et al. (2020), the ReSOLVE framework created by the Ellen MacArthur Foundation (2017) is used.

3.2.3 Reporting the Review

Phase 8

This phase can be divided into two central activities: descriptive and thematic analysis (Tranfield, Denyer & Smart, 2003). According to the authors, the former analysis focuses on providing statistical information about the included studies such as country of publication, journal, industry, or year published, among others. Furthermore, the authors state that the research report should also include a thematic analysis that encompasses the core contributions from the selected literature by identifying and linking emerging trends, patterns, and themes. The results from both activities carried out for this thesis are showcased in Section 4.

Phase 9

The last phase of the reporting stage, 'Phase 9', is about getting the evidence obtained from the research into practice (Tranfield, Denyer & Smart, 2003). The central idea stated by Tranfield, Denyer & Smart (2003) is to create tools for practitioners to make evidence-informed decisions based on the context, personal experience, and problem-solving skills. For this thesis, a set of technological adoption pathways that enable the adoption of circularity practices along the value chain is presented in Section 5.

3.3 Interviews

3.3.1 Expert Interviews

According to Bell, Bryman & Harley (2018), one of the most utilised methods in qualitative research is the interview. This is primarily because of its focus on detail and richness of the answers obtained by the researcher – a handy set of characteristics that are looked upon when conducting exploratory research (Bell, Bryman & Harley, 2018). Within the category of interviews, the semi-structured type provides a greater balance between flexibility and control of the interview process by defining a list of topics or issues to be asked by the interviewer while also letting the interviewee elaborate on his or her points of interest (Denscombe, 2017).

Within the qualitative interviews method, 'expert interviews' are a widely-used tool in the social sciences research field (Döringer, 2021). The core idea behind this empirical research tool is to explore an expert's knowledge (Meuser & Nagel, 2009). The method is often used when the interviewer is "aiming at gaining information about or exploring a specific field of action." (Döringer, 2021, p.265). According to Kolb (2008), it is also a valuable mechanism to "gather factual information about a problem from someone with a specific product, consumer or industry knowledge." (p.146).

Therefore, with the objective of getting a broader and practical-oriented understanding of the phenomenon in question, this thesis complements the systematic literature review analysis with a set of qualitative, semi-structured interviews. These interviews are conducted to professional practitioners or 'experts', whose job position is related to one or more of the manufacturing stages of the plastic materials value chain.

3.3.2 Sampling Strategy

Denscombe (2017) highlights that the point of the exploratory sample is to "provide the researcher with a means for generating insights and information." (p.33). Considering the scale, objectives, and explorative approach of the current thesis research, when it comes to the purpose of the sample selection, an exploratory sample is used for this thesis. Regarding the basis for the sample selection, a non-probability sampling strategy is utilised in the current research. The reason behind this decision relates to time and resources constraints that must be allocated to pursue a probability sampling which would fall out of the scope of the present research project.

Furthermore, intending to get the most relevant and knowledgeable input for the research in question, this thesis uses a purposive type of sampling (Denscombe, 2017, p.41). According to Denscombe (2017), this sampling approach is useful when the researcher already knows something about the topic and focuses on interviewing the individuals that might produce the most valuable data. From the scouting search performed for the systematic review, a clear picture of the actors and entities involved in the plastic materials value chain is formulated, so the search for potential experts to be interviewed is based upon their expertise on either one specific stage (e.g. polymer producer) or a high-level understanding of this chain (e.g. external consultants or academics). The following subsection describes the selection criteria used in the interviews.

3.3.3 Selection Criteria

For the selection of interviewees, a set of four questions is used to determine if the candidate's profiles are relevant and knowledgeable to be included in the sample:

1. Is the interview candidate currently working or has previously worked at a company involved in the manufacturing stages of the plastic materials value chain?
2. Is the interview candidate currently working or has previously worked within the sustainability, supply chain, or innovation areas of a company?
3. Is the interview candidate's company actively engaged in the improvement of its environmental footprint?
4. Is the current job position of the interview candidate performing at a mid-level or above position?

3.3.4 Data Collection

<u>*Participant's reach out*</u>

A total of eight interviews were performed between the months of April and May 2021. To achieve this number of sessions, several paths were followed to contact and schedule the interviews. Figure 7 details the process and outcomes of this activity.

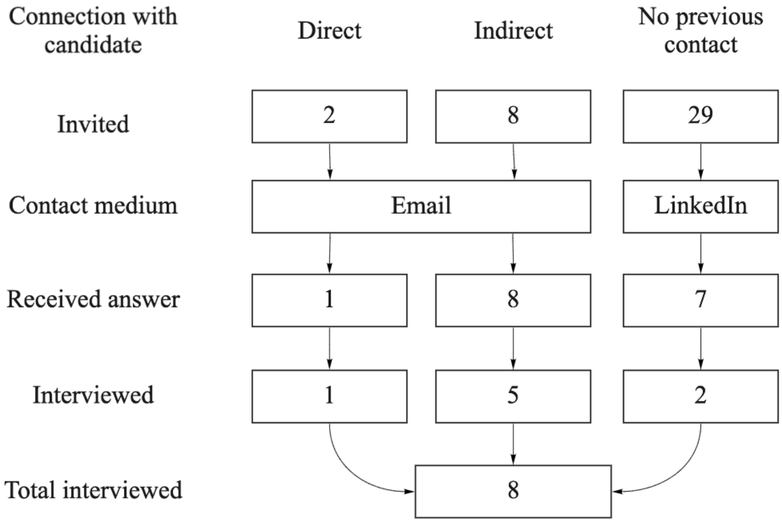


Figure 7. Participant's Reach Out Process.

The profiles of the interviewees and details of the interviews are detailed in Table 8.

Table 8. Interview's Details and Participants Profiles.

Code	**Organisation & Interviewee**					**Interview**	
	Company Type	**Industry**	**Company HQ/Branch**	**Current Position**	**Department**	**Date**	**Length**
B1	Brand	Food Production	Sweden	Global Engineering & Automation	Supply Chain	19/04	62:20
B2	Brand	Consumer Goods	USA	*Go-To-Market Transformation	Supply Chain / Innovation	19/04	40:42
C1	Consultancy	Management Consulting	Netherlands	Consultant	Sustainable Organisation & Environment	20/04	66:47
P1	Polymer Producer	Chemicals	Netherlands	Program Manager	Sustainability	20/04	54:57
S1	Sustainability Certification Entity	Safety & Environment	USA / Sweden	**General Manager	Global Accounts	21/04	57:26
A1	University	Academia	Sweden	Researcher	Environment & Innovation Studies	27/04	62:08
P2	Polymer Producer	Chemicals	Germany	Global Product Manager	Advanced Materials	29/04	31:52
B3	Brand	Retail	Sweden	Material & Innovation Area Manager	Textiles	10/05	46:45

Notes:
* Has relevant previous professional experience on the supply chain and sourcing departments.
** Has relevant previous professional experience on the plastic raw materials supply chain.

Conducting the interview

The interviews followed a guided strategy based on the predefined questions and structure showcased in the interview guide (Bell, Bryman & Harley, 2018) (see Appendix D). Additional to the guidance provided, one of the advantages of developing and using an interview guide is to exploit an interview's and its participants potential while steering the conversation towards the research topics (Bell, Bryman & Harley, 2018). During the development of this guide, a pilot interview was performed with a former classmate and coworker to improve its quality and receive feedback regarding the clarity and order of ideas to be conveyed.

Moreover, to allow for the participants to prepare their answers, the main questions to be addressed were shared a few days before the session. Although these questions served as a guide, the interviews were carried out in a conversational format, leaving space for the interviewees to elaborate on their key points and even divert to related topics when relevant.

All interviews were conducted in an online setting through the software packages Zoom and Microsoft Teams. To guarantee confidentiality and confirm recording consent by the participants, a message in the Zoom application was displayed before the interviewee joined the virtual meeting. When this was not the case (due to an upgrade of software version requirements), a verbal confirmation was carried out during the first minutes of the session, as described in the interview guide (Appendix D).

3.3.5 Data Analysis

Following the suggestion by Bell, Bryman & Harley (2018), all interviews were recorded and transcribed. This allowed for a more fluent and focused interview since the interviewer (myself) was more engaged in the conversation and was able to ask follow-up questions. The paid version of the software 'Otter', which enables an automated and artificial intelligence assisted transcription, is used. The writings were further confirmed through a manual inspection of each interview. Although a lengthy task, this activity ensures the quality and meaning of the conversations.

As stated before, the expert interviews methodology is a supplement of the systematic review, which stands as the primary data and analysis method. Hence, with the objectives of unifying both data sources into one same analysis stream and narrowing down the scope of this thesis considering the resources and time available, the data and results from the expert interviews are added into the systematic review main framework of analysis (ReSOLVE framework).

Nonetheless, a high-level analysis of the most common terms mentioned by the interviewees is presented. The interviews are grouped based on the type of company, resulting in the following categories and participants: 'Brands' (B1, B2, and B3), 'Producers' (P1 and P2), and 'Others' (A1, C1, S1). The software NVIVO was used to retrieve the Top 100 terms for each group and in an aggregate manner. To obtain a list of relevant words to the topic in question, only words with a minimum of 2 letters are considered, and irrelevant words are left out of the ranking on purpose (e.g. much, lot, very, because, business, call, definitely, here, their, instead, myself, name, one, piece, right, something, thing, among many others). Lastly, word variations are grouped under the same term; for example, 'waste', 'wasteful', 'wastefully', 'wastes', and 'wasting' are grouped under the word 'waste'.

3.4 Methodological Limitations

As with any research project, the methodologies here presented have limitations that should be taken into consideration.

From the systematic review, there are two primary limitations that Denscombe (2017, p.142) mentions. First, this method only considers the findings from studies that have been published or that are publicly available. Meaning that findings which, for whatever reason are not published, are not covered through this method and therefore, there might be a considerable portion of valuable information that is not included. In terms of this thesis, since it considers only the scientific and peer-reviewed publications, there is a vast source of information left outside of the scope and can be summarised as grey literature. However, the idea of complementing the research with expert interviews helps to, at least partially, overcome this issue. Second, since research in the social sciences generally does not focus on the same topic, procedure, or sample, it makes it difficult to compare and evaluate data in a direct manner. Although this certainly is a limitation for the current thesis, the taken approach aids in surpassing this matter by following a thematic approach rather than a direct comparison or quantitative aggregation of the included research findings.

Regarding the limitations of the interviews, both Denscombe (2017, p.202) and Bell, Bryman & Harley (2018, p.458) provide several points applicable to qualitative interviews. The most relevant for this thesis are detailed next. First, the researcher's influence or "interviewer effect" (Denscombe, 2017, p.202) while conducting the interview might affect both the answers given by the interviewee and the interpretation of these statements. This thesis addresses the issue by providing a detailed process for the conduction and moderation of the interview (see Appendix D) as well as following the advice by Denscombe (2017) in regards to the way of carrying out an unbiased, transparent, and non-judgemental line of questioning during the interview session (p.191).

Another relevant limitation put forward by both authors (Denscombe, 2017; Bell, Bryman & Harley, 2018) relates to the lack of a 'naturalistic' setting and the inhibitions that this supposes. In this thesis' interviews, the strategy to reduce the impact of this effect was to follow a conversational approach to achieve a more natural exchange of ideas. Moreover, to minimise the interviewee's inhibition, the researcher stated, since the beginning of the interview, that no other person except for the researcher will have access to the interview's recordings or transcripts and that their participation is completely anonymous. As part of the ice-breaking technique, communicating that "there is no right or wrong answer" to the questions asked also helped.

Lastly, Bell, Bryman & Harley (2018) highlight the fact that this type of interviews "provide limited insight into social interactions and behaviours." (p.459). Although this is an important point, the focus of this research is to understand a phenomenon from different perspectives meaning that the statements and opinions from the interviewees will serve as a complement to the findings of the systematic review and vice versa. Thus, even though there will be behaviours and social interactions omitted, following this mixed strategy helps to minimize the data left out.

4 Results

This section presents the results and analysis of the research starting with a descriptive analysis of the systematic review. It then expands with the thematic analysis, where the ReSOLVE framework is used to synthesise the information obtained from both the systematic review and the expert interviews.

4.1 Descriptive Analysis

4.1.1 Articles

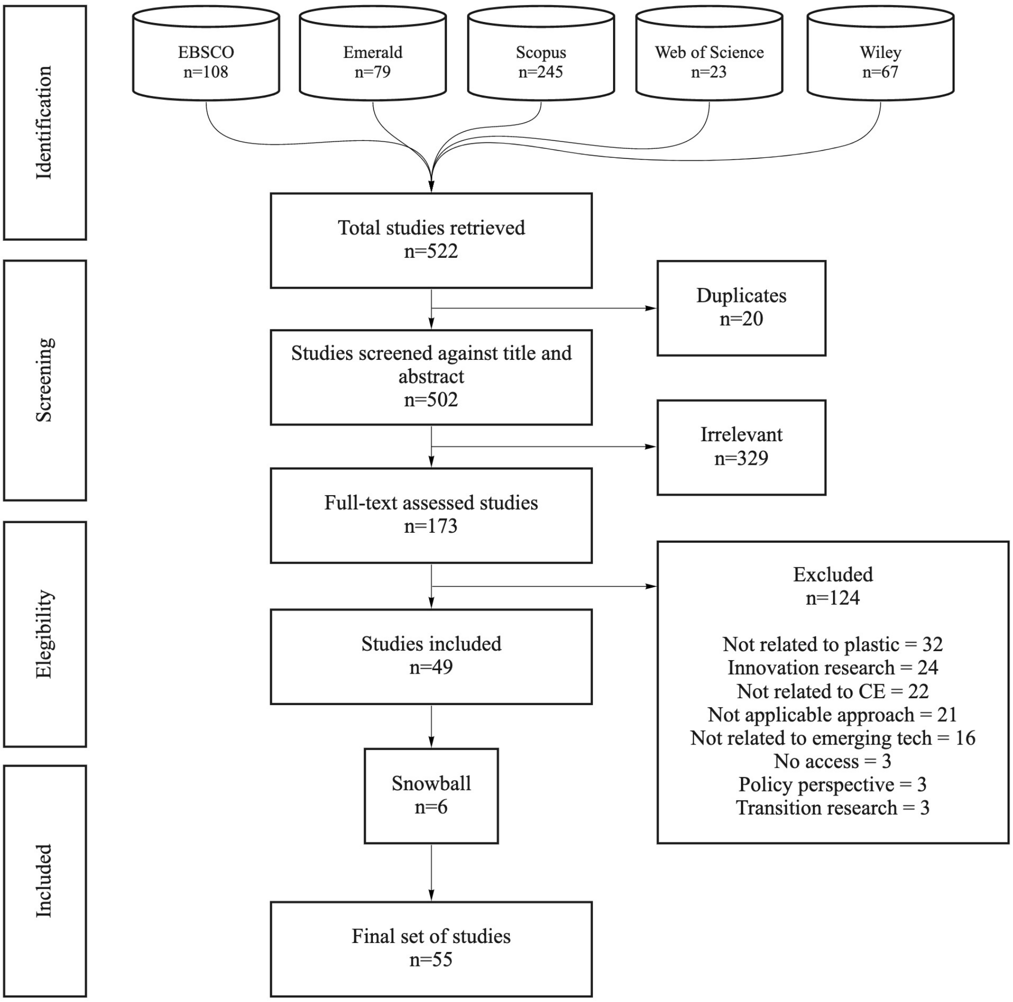


Figure 8. PRISMA Diagram.
Information flow diagram with Preferred Reporting Items for Systematic Reviews and Meta-Analyses. Own data. Diagram adapted from Mohen et al. (2009).

A total amount of 522 papers were retrieved from the five databases detailed in the Methodology section. From the 'screening' activity, 20 duplicates and 329 papers marked as irrelevant were discarded, resulting in 173 studies assessed in a full-text manner. During the 'eligibility' activity, 124 articles were dropped for several reasons detailed in Figure 8, leaving a total of 49 articles to be included in the review. Lastly, based on the reference list of this last set of studies, six additional papers were included in the review, resulting in a total of 55 studies to be extracted and analysed in this thesis. Figure 8 details the process here described. Table 9 enlists the final set of articles included in this thesis' systematic review.

Table 9. List of Reviewed Articles.

#	**Title**	**Authors**
1	Applying Industry 4.0 technologies in the COVID-19 sustainable chains	Acioli, Scavarda & Reis (2021)
2	Practical Eco-Design and Eco-Innovation of Consumer Electronics--the Case of Mobile Phones.	Andrae et al. (2016)
3	Remodeling agro-industrial and food wastes into value-added bioactives and biopolymers	Arun et al. (2020)
4	Industry 4.0 and supply chain sustainability: framework and future research directions	Bag et al. (2018)
5	Barriers to adoption of blockchain technology in green supply chain management	Bag et al. (2021)
6	Biopolymer-based nanocomposite films and coatings: recent advances in shelf-life improvement of fruits and vegetables	Basumatary et al. (2020)
7	Circular futures: What Will They Look Like?	Bauwens, Hekkert & Kirchherr (2020)
8	Resources, collaborators, and neighbors: The three-pronged challenge in the implementation of bioeconomy regions	Bezama et al. (2019)
9	Fabricating Futures and the Movement of Objects.	Birtchnell & Urry (2013)
10	Blockchain for the Circular Economy: Analysis of the Research-Practice Gap	Böckel, Nuzum & Weissbrod (2021)
11	Process intensification connects scales and disciplines towards sustainability	Boffito & Fernandez Rivas (2020)
12	Industry 4.0 Disruption and Its Neologisms in Major Industrial Sectors: A State of the Art	Bongomin et al. (2020)
13	Managerial and Industry 4.0 solutions for fashion supply chains	Braglia et al. (2021)
14	Understanding the views of the UK food packaging supply chain in order to support a move to circular economy systems	Clark, Trimingham & Storer (2019)
15	Synthetic biology - pathways to commercialisation	Clarke (2019)
16	An integrated approach to electronic waste (WEEE) recycling	Dalrymple et al. (2007)
17	In the business of dirty oceans: Overview of startups and entrepreneurs managing marine plastic	Dijkstra, van Beukering & Brouwer (2021)
18	End-to-end collaboration to transform biopharmaceutical development and manufacturing	Erickson et al. (2021)
19	Current trends in the production and applications of torrefied wood/biomass - A review	Eseyin, Steele & Pittman (2015)
20	Blockchain for the future of sustainable supply chain management in Industry 4.0	Esmaeilian et al. (2020)
21	Valuable Compound Extraction, Anaerobic Digestion, and Composting: A Leading Biorefinery Approach for Agricultural Wastes	Fermoso et al. (2018)
22	Recovery of Natural Antioxidants from Agro-Industrial Side Streams through Advanced Extraction Techniques.	Fierascu et al. (2019)
23	Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold?	Garmulewicz et al. (2018)

24	SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers.	Gligoric et al. (2019)
25	A research challenge vision regarding management of agricultural waste in a circular bio-based economy.	Gontard et al. (2018)
26	Building trust and equity in marine conservation and fisheries supply chain management with blockchain	Howson (2020)
27	Waste to energy and circular economy: the case of anaerobic digestion	Hussain, Mishra & Vanacore (2020)
28	Circular economy approach to recycling technologies of post-consumer textile waste in Estonia: a review.	Hussain et al. (2021)
29	Towards the Circular Economy: Converting Aromatic Plastic Waste Back to Arenes over a Ru/Nb2O5 Catalyst	Jing et al. (2021)
30	A conceptual framework for barriers of circular supply chains for sustainability in the textile industry	Kazancoglu et al. (2020)
31	Shaping digital sustainable development in chemical companies	Keller & Bette (2020)
32	Blockchain and the circular economy: potential tensions and critical reflections from practice	Kouhizadeh, Zhu & Sarkis (2020)
33	Exploring the future of the bioeconomy: An expert-based scoping study examining key enabling technology fields with potential to foster the transition toward a bio-based economy	Laibach, Börner & Bröring (2019)
34	Value-added processing of crude glycerol into chemicals and polymers	Luo et al. (2016)
35	Conceptualization of a spent coffee grounds biorefinery: A review of existing valorisation approaches.	Massaya et al. (2019)
36	Supercritical CO2 impregnation of PLA/PCL films with natural substances for bacterial growth control in food packaging	Milovanovic et al. (2018)
37	Assessing the potential of biowaste for bioplastics production through social network analysis	Morone, Tartiu & Falcone (2015)
38	Use of bio-based polymers in agricultural exclusion nets: A perspective	Mukherjee et al. (2019)
39	Current status of biobased and biodegradable food packaging materials: Impact on food quality and effect of innovative processing technologies	Nilsen-Nygaard et al. (2021)
40	Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management	Nižetić et al. (2019)
41	The Emergent Role of Digital Technologies in the Circular Economy: A Review	Pagoropoulos, Pigosso & McAloone (2017)
42	Circular bioeconomy and integrated biorefinery in the production of xylooligosaccharides from lignocellulosic biomass: A review	Pinales-Márquez et al. (2021)
43	Resource recovery from wastewater by biological technologies: Opportunities, challenges, and prospects	Puyol et al. (2017)
44	Digital technologies catalyzing business model innovation for circular economy - Multiple case study	Ranta, Aarikka-Stenroos & Väisänen (2021)
45	Blockchain technology and its relationships to sustainable supply chain management	Saberi et al. (2019)
46	The science of microrecycling: a review of selective synthesis of materials from electronic waste	Sahajwalla & Hossain (2020)
47	Urban biorefinery for waste processing	Satchatippavarn et al. (2016)
48	Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options	Sovacool et al. (2021)
49	Organic waste to biohydrogen: A critical review from technological development and environmental impact analysis perspective	Tian et al. (2019)
50	Circular Economy, 3D Printing, and the Biosphere Rules	Unruh (2018)
51	Beyond Mechanical Recycling: Giving New Life to Plastic Waste	Vollmer et al. (2020)
52	Sustainability outcomes of green processes in relation to industry 4.0 in manufacturing: Systematic review	Vrchota et al. (2020)
53	Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review	Wu & Montalvo (2021)

54	Mobilising information systems scholarship for a circular economy: Review, synthesis, and directions for future research	Zeiss et al. (2021)
55	Let the Biocatalyst Flow	Žnidaršič-Plazl (2021)

4.1.2 Publication Year

While the publication years of the included articles range from 2007 until 2021, 83% are published in the last three years. This reflects the field's novelty in the academic realm and is aligned with the rising attention towards the development of theoretical and practical tools to address the environmental issues (i.e. climate change) that stalks humanity.

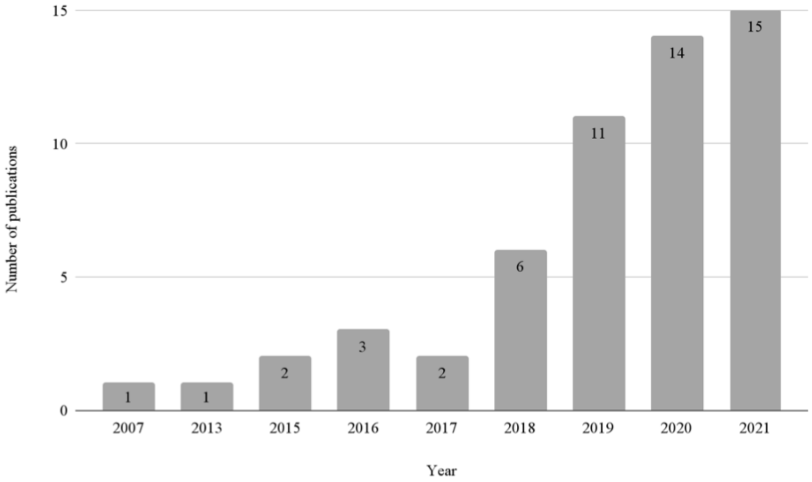


Figure 9. Publication Years of Included Articles.

4.1.3 Geographic Spread

The authors of the included publications are affiliated to a wide range of research institutes with a total of 38% of these studies written by authors who collaborate with academic colleagues that are affiliated to research centres located in a different country. This result adds up to the evidence behind the growing and widespread interest of researchers in the topic. When examining the articles published by researchers from an individual country basis, the United Kingdom and the United States represent the two largest sources of publications of the included studies accounting for 12% and 14%, respectively. Worth mentioning is the under-representation of authors affiliated to institutes in developing economies (IMF, 2020) which account for only four studies of the total sample.

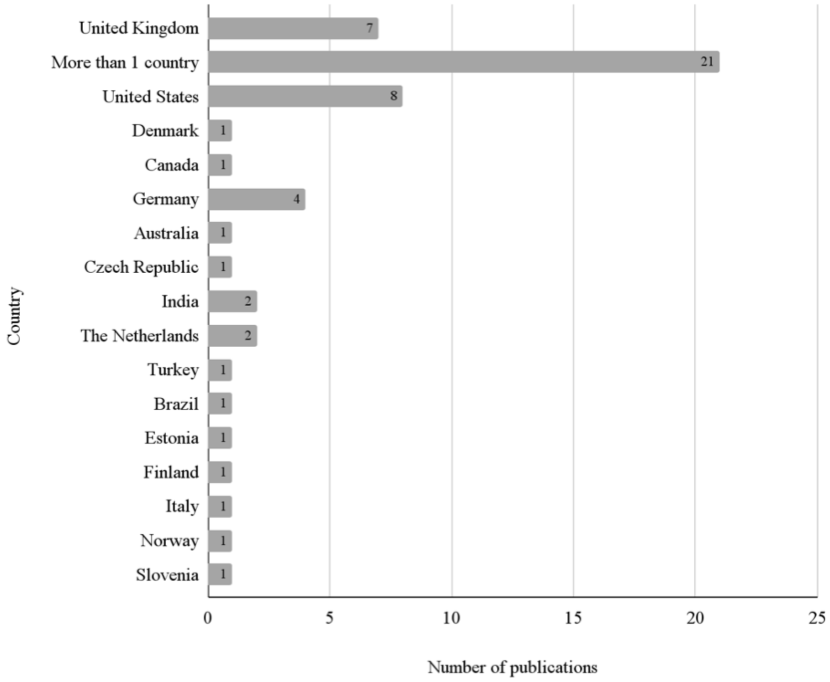


Figure 10. Geographic Spread of Included Articles.

4.1.4 Industries

The pervasiveness and vast number of applications of plastic materials in the reigning socio-technical system are reflected in the industry share of the included studies. The largest share is obtained by studies that do not specify an industry of focus but instead talk about plastic materials from a general perspective. Secondly, the 'Agro-Food' category represents such a large portion since several studies talk about the concept of 'bioeconomy' which is principally related to organic waste management (and thus, the agricultural activities) but also because this category considers the studies related to food packaging, one of the common uses of plastic materials. The 'chemicals' and 'plastic' categories, although related, are differentiated by the authors in their corresponding studies.

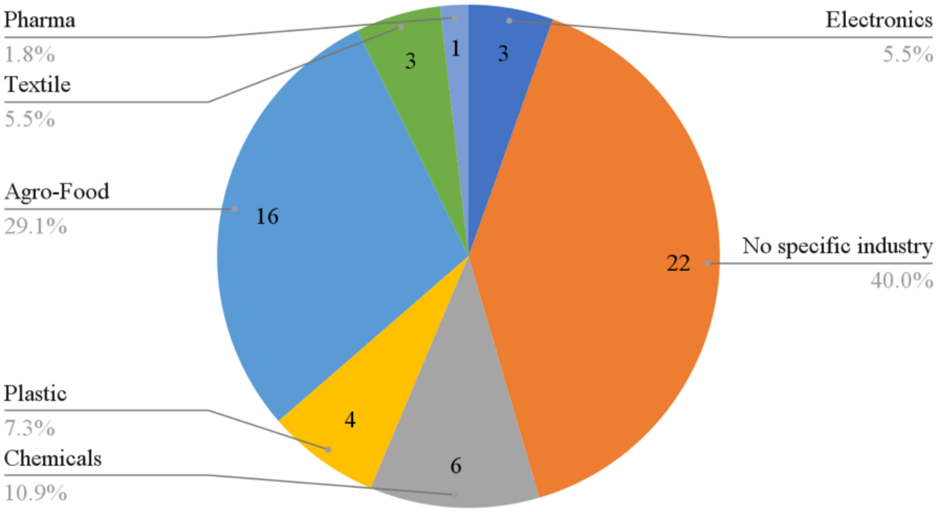


Figure 11. Related Industry of the Included Articles.

4.1.5 Knowledge Field

The study of the phenomenon in question (transition towards a circular economy in the plastics materials value chain) is based on a wide range of disciplines that includes natural sciences (i.e. biology), physical sciences (i.e. chemistry), social sciences (i.e. business, economics), and information sciences (i.e. IT), among others. Interestingly, a combination of these knowledge domains yields several fields such as environmental sciences and engineering, biochemistry, or biotechnology. Concepts such as ‘biorefinery’, ‘bioeconomy’, ‘industrial symbiosis’, or ‘synthetic biology’ are examples of the cross-fertilisation process that these disciplines are going through. A complete list of the included articles with the journal of publication and knowledge field can be found in Appendix E.

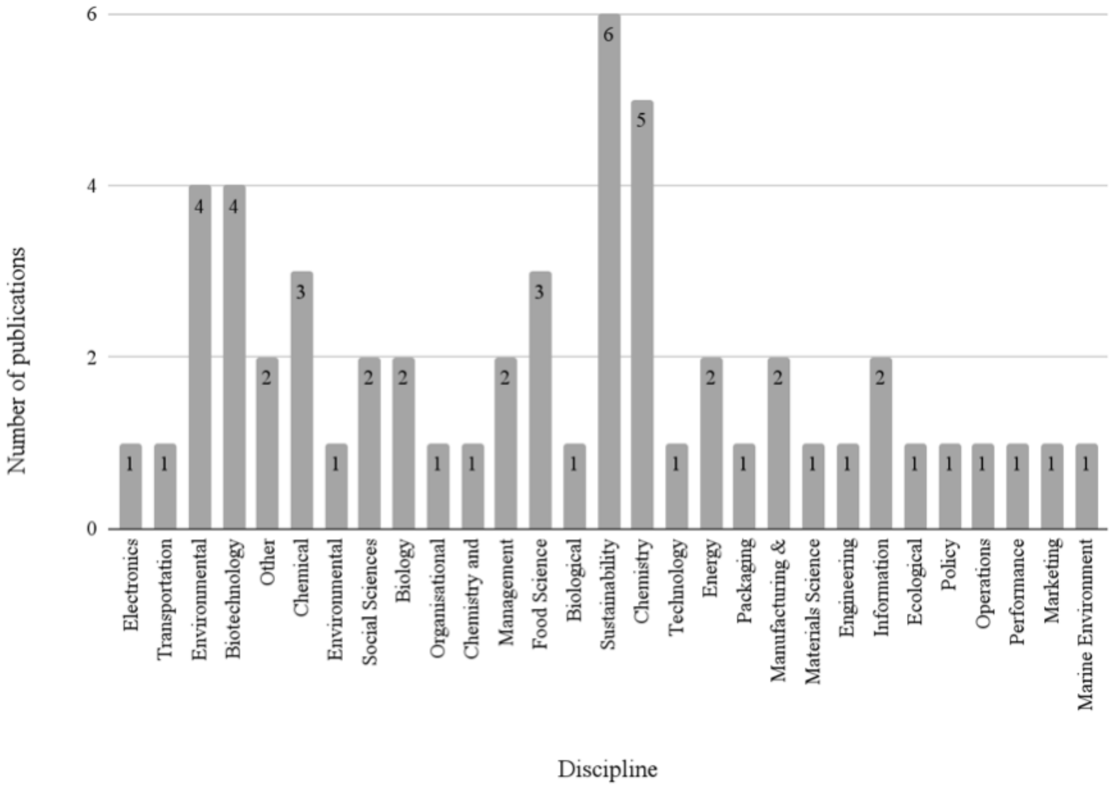


Figure 12. Journal’s Knowledge Field of the Included Articles.

4.1.6 Emerging Technologies

A total of 13 emerging technologies related to the transition towards circularity in the plastic materials value chain were identified in the included literature. The largest shares relate to the categories of ‘Waste-to-X’ and ‘Biotechnologies’, which play a fundamental role in the aforementioned transition. Interestingly, although emerging, these technologies are not related to the information technologies (IT) field, but instead, they are more closely associated with the chemistry and biology fields. Nonetheless, their proper functioning as enablers of circularity in the plastic value chain depends on the development and spread of the technologies that are most commonly grouped under the name of 'Industry 4.0': Blockchain, Artificial Intelligence (AI), 3D Printing (or Additive Manufacturing), Internet of Things (IoT), Nanotechnologies, Big Data (or Big Data Analytics), Cloud Computing, Robotics, and Augmented & Virtual Reality. Each of these technologies are also mentioned in the articles. Lastly, 'Chemical Recycling' and 'Process Intensification' also play an important role that is showcased in the Thematic Analysis section.

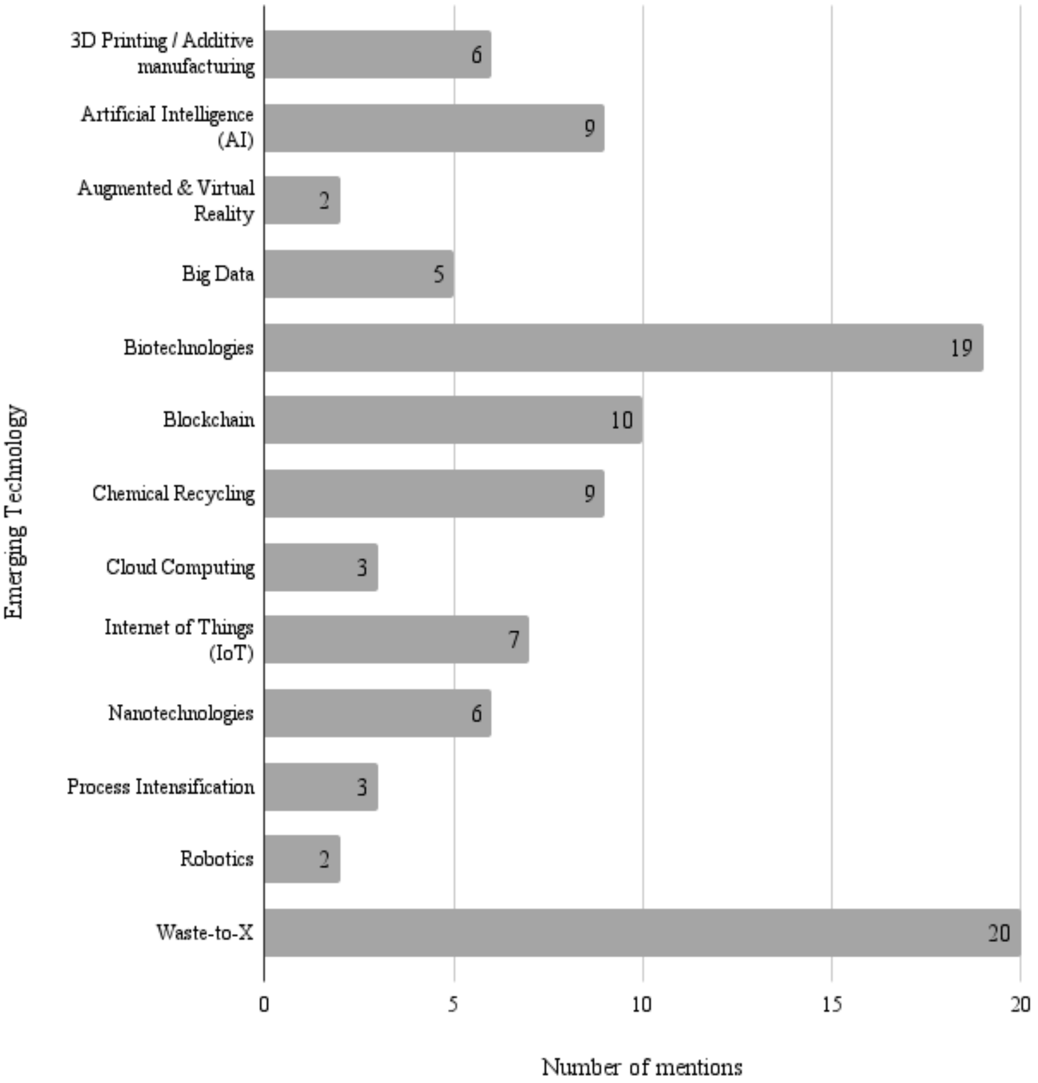


Figure 13. Emerging Technologies Mentioned in the Included Studies.
Note: The total number of mentions are more than the 55 included papers since almost every paper included mentioned more than one technology.

4.1.7 Features

The identified technologies can be associated to certain features or characteristics that make possible the transition towards a CE. While some of these features more closely relate to a specific emerging technology (e.g. *blockchain*-enabled transparency), other characteristics are associated to more than one emerging technology, for example, both *biorefineries* and *chemical recycling* make CE feasible. Moreover, a set of technologies can relate to more than one feature, for instance, *Industry 4.0* technologies enable higher efficiency and performance levels along the plastic value chain.

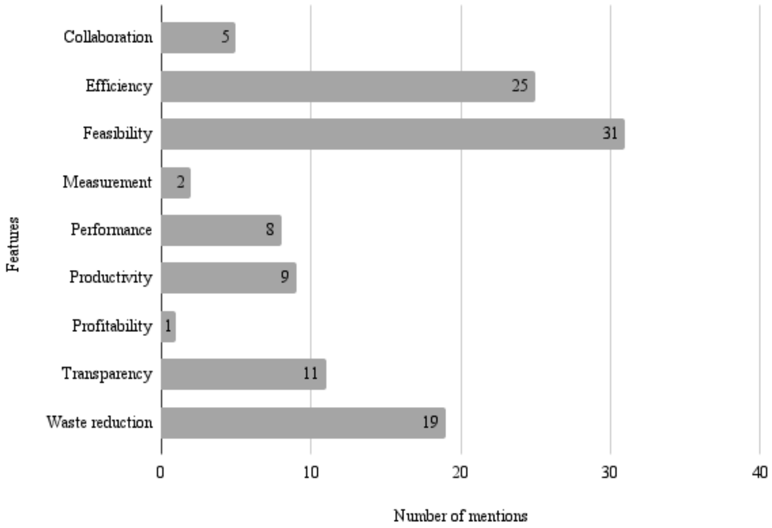


Figure 14. Features of the Emerging Technologies Identified in the Included Articles.
Note: The total number of mentions is more than the 55 included papers since almost every paper included mentioned more than one technology, and thus, more than one feature as well.

4.1.8 Impact on the Plastic Value Chain Stages

Mainly derived from the focus of this research, the reviewed articles relate to the non-consumer steps in the plastic value chain. Interestingly, several papers present technologies that impact all the stages in the value chain and therefore, they could indicate a possible system-level change.

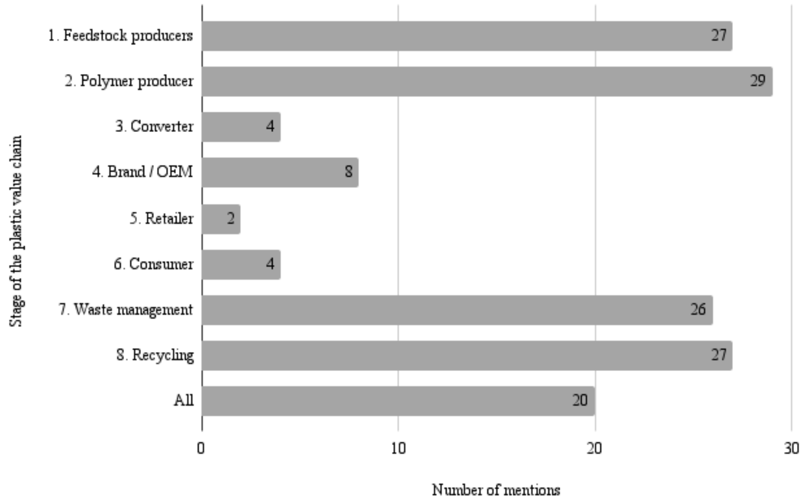


Figure 15. Stages of the Plastic Value Chain Impacted by the Emerging Technologies Identified in the Included Articles.
Note: The total number of mentions is more than the 55 included papers since almost every paper included mentioned more than one technology, and thus, more than one feature as well.

4.1.9 Interview’s Most Frequent Terms

The last element of the descriptive analysis concerns a high-level exploration of the most frequently used terms in the expert interviews where a couple of interesting facts are worth pointing out. The top positions are mostly occupied by the same words among the three groups of participants (‘Brands’, ‘Producers’, ‘Others’), but some key terms do exhibit considerable differences in placement depending on the type of companies they represent. Figure 16 shows the Top 100 terms mentioned in the interviews in an aggregate manner.

Figure 16. Top 100 Word Count - All Interviews.

The term ‘recycling’ appears as the first and second most mentioned word for ‘Producers’ and ‘Others’, respectively, but for ‘Brands’, it is located in position 44. This might indicate a lack of accountability along the recycling process on behalf of brands compared to the producer entities. This result aligns with the fact that the term ‘chemical’ achieves relatively high positions for the ‘Producer’ (5) and ‘Others’ (19) categories, while for ‘Brands’, it fails to make it even to the Top 100 terms. A similar logic applies to the term ‘sort’, placed in the 5th position for the ‘Others’ category, but it is barely mentioned by ‘Brands’ (position 96) and fails to appear in the Top 100 from the ‘Producer’ perspective. Likewise, this could reflect a lack of visibility from the different actors involved in the steps along the plastic value chain.

Another interesting example is the term ‘circular’ which achieves a significantly higher position (15) in the ‘Others’ group when compared to the position achieved in the ‘Brands’ (33) and ‘Producers’ (34) groups. Lastly, the term ‘cost’ has a similar position in both ‘Brands’ (26) and ‘Producers’ (32), but it does not accomplish to be within the Top 100 for ‘Others’. A possible interpretation of this case could be related to the diverse perspectives these two broad groups have in relation to the transition towards circularity – brands and producers see the value of transitioning, but the economic cost of it plays a vital role in the decision. The complete table with the Top 100 terms for each analysed group of interviewees can be found in Appendix F.

4.2 Thematic Analysis

As detailed in Section 3, with the primary purpose of getting a better understanding of the phenomenon in question, this thesis combines the insights from both data sources in a joint thematic analysis (see Figure 4).

The following categories are based on the ReSOLVE framework (EMF, 2015) which provides a structure for the analysis of both data inputs. This framework is used in a couple of articles found in the systematic review process (Kouhizadeh, Zhu & Sarkis, 2020; Ramirez-Peña et al., 2020) and provides a business-oriented categorisation and operationalisation of the CE principles previously detailed (EMF, 2015, p.22):

1. Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
2. Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles
3. Foster system effectiveness by revealing and designing out negative externalities

4.2.1 Regenerate

The 'Regenerate' action area relates to the restoration of the Earth's natural cycles and ecosystems. Therefore, it signifies one of the most transformative action areas of this framework when thinking about the current systemic dynamics (Section 5 elaborates on this idea). The Ellen MacArthur Foundation (2015) breaks it down into the three sub-areas presented next.

Shift to renewable energy and materials

The concept of 'bioeconomy' is repeatedly mentioned in the systematic review (Bezama et al., 2019; Laibach, Börner & Bröring, 2019; Pinales-Márquez et al., 2021) as it relates to the "production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products, and bioenergy." (European Commission, 2012, p.9).

To better process and analyse the data, and considering the different perspectives that the included literature puts forward, the concept is divided in two. Whereas the analysis in this action area focuses on the former part of the aforementioned definition (production of renewable biological resources), the technologies that enable the transformation of waste into value-added products (the latter part of the definition) are discussed in the 'Loop' action area (Subsection 4.2.4).

When it comes to the plastic materials industry, the technologies behind the production of bio-based polymers such as PLA, PCL, or PHA are currently being tested (Interview B2; Interview S1), scaled (Interview P1; Interview S1), and increasingly providing an economically and environmentally viable platform for the substitution of fossil-based plastics

(Sovacool et al., 2021). Nilsen-Nygaard et al. (2021) exhibit the different types of bio-based and biodegradable polymers currently available (Table 10). The agriculture industry showcases a compelling case with the use of agricultural nets made out of biopolymers to increase crop yields and minimise the use of direct contact pesticides while also minimising the amount of plastic waste (Mukherjee et al., 2019). Interviewees B2, P1, and S1 also detail how their companies are pushing towards a change towards the use of biopolymers in the furniture, food, and automotive industries.

Table 10. Bio-based and Biodegradable Polymers.
Adapted from Nilsen-Nygaard et al. (2021, Fig.1).

Synthetic Biopolymers Synthesised from bio-derived monomers	**Microbial Biopolymers** Produced by microorganisms	**Natural Biopolymers** Extracted from biomass
Synthetic Polyesters Polylactic Acid Poly(butylene succinate) Poly(butylene succinate) adipate	Microbial Polyesters Polyhydroxyalkanoates	Polysaccharides Alginate Carrageenan Cellulose Chitosan Pectin Starch
	Exopolysaccharides Bacterial cellulose Bacterial alginate Xanthan	Proteins Casein Gelatin Soy protein Zein

Within the 'bioeconomy' sphere, the lines between areas of science become blurry. Since bioplastics are fabricated from organic feedstock or biomass, a merge between chemistry and biology is evident. Clarke (2019) talks about the *synthetic biology* field and describes how it enables the use of photosynthesis to capture solar energy and generate the building blocks of the bioeconomy materials. In this sense, he states, gene editing of crops and plants to confer desired characteristics during the harvest (e.g. pesticide-free crops – Luo et al., 2016), production processes (e.g. biocatalysts – Žnidaršič-Plazl, 2021) and final products (e.g. anti-fungal properties) are not only possible but critical paths to overcome future large-scale production challenges.

However, aside from the high-technology development perspective, system-wide work needs to be done for the bio-based and renewable materials industry to properly expand. Bezama et al. (2019) highlight the importance of sustainable feedstock availability at the regional level, the collaboration between supply chain actors (Interview P1; Interview S1), and the acceptance of biotechnologies in the current social system for the bioeconomy model to prosper. To this, Laibach, Börner & Bröring (2019) add the importance of agricultural performance improvement and the more efficient use of biomass where the circular economy concept is included. Furthermore, a shift towards renewable energy sources to be used in the manufacturing processes also plays a key role as it lowers the final product carbon footprint (e.g. in food products – Sovacool et al., 2021) and thus, increasing its customer appeal.

Reclaim, retain, and regenerate the health of ecosystems

Restoring the balance of disrupted ecosystems is a fundamental aspect of the circular economy. As a result of waste mismanagement and a lack of recyclability, oceans, reefs, and rivers are among the most impacted ecosystems by plastic waste (Thushari & Senevirathna, 2020; Sutherland, DiBenedetto & Bremer, 2021), and the problem is of great magnitude. From the systematic review, two papers link to this issue.

Dijkstra, van Beukering & Brouwer (2021) analyse the marine plastic waste startup sphere and categorise the innovations and technologies into four areas that contribute to the ocean ecosystem regeneration: prevention, collection, transformation, and monitoring. The prevention side focuses on the development of marine degradable plastics (i.e. *bioplastics*) and the avoidance of microplastics or floating plastic debris to enter the ocean from consumer or industrial wastewater. On the collection grounds, one of the most challenging ones, drones and automated robots are used to remove plastics from beaches and nearshore environments. The transformation category involves using collected plastics to produce new materials, energy, or other products. The advances in this area are among the most important, considering that collected plastic from the ocean often goes to landfill according to Schneider et al. (2018). *Mechanical* and *chemical recycling* technologies to produce fishing nets, construction blocks, energy (through *pyrolysis*), or new polymers with similar properties to those produced from virgin sources are showcased as promising solutions to the problem (Interview S1). Lastly, from the monitoring perspective, technologies such as *blockchain* and mobile apps directed to final consumers can provide the much-needed traceability and cluster location of plastics waste, an idea further developed by Howson (2020) and Zeiss et al. (2021).

In the paper by Howson (2020), a series of *blockchain-enabled systems* to tackle marine plastic waste from a socioeconomic perspective are presented. The central idea is to build trust and equity along the several links of the fisheries supply chain to achieve optimal levels of marine ecosystems' conservation. Some of the features presented relate to providing transparency for consumers to be confident of the fish product's provenance, for charities and NGOs to be sure that their donations are being well-employed, and for seafood producers to be able to show their sustainability-oriented practices.

Return recovered biological resources to the biosphere

Although not precisely aligned with the concept of this sub-area, the return of elements such as nitrogen and phosphorus to the biosphere through the recycling of wastewaters and biowaste is part of the outputs of a biorefinery, a concept detailed on the 'Loop' action area (Subsection 4.2.4).

4.2.2 Share

The 'Share' action area focuses on the reuse and sharing of assets and products as well as extending the overall product's life (EMF, 2015). In other words, it emphasises the importance of the inner loops in the circular economy model, and it can be disaggregated into the following sub-areas here detailed.

Share assets & Reuse / Second Hand

Considering the relatedness of both sub-areas ('Share assets' and 'Reuse/Second Hand') and the relatively low quantity of articles reviewed that talk about either of the topics, these are merged into the same category.

The 'sharing economy' concept, that is, the sharing, exchanging, rental or collaborative consumption of products and services between consumers (C2C) using information technologies as enablers (Puschmann & Alt, 2016; Zeiss et al., 2021) adheres to this sub-area. While Vrchota et al. (2020) and Zeiss et al. (2021) point out the role of digital technologies as enablers of this business model, they do not discuss any specific emerging technology or step in the plastic materials value chain.

Blockchain is the most mentioned emerging technology in the articles from the systematic review due to its capabilities to trace assets or products along the sharing/consumption journey (Bauwens, Hekkert & Kirchherr, 2020; Böckel, Nuzum & Weissbrod, 2021; Esmaeilian et al., 2020), and for its security, recordkeeping, and immutability of information features (Kouhizadeh, Zhu & Sarkis, 2020). Additionally, Gligoric et al. (2019), Pagoropoulos, Pigosso & McAloone (2017), and Kouhizadeh, Zhu & Sarkis (2020) discuss the physical location tracking benefits that *IoT* technologies provide. The mix of these two technologies (*blockchain* and *IoT*) facilitate the sharing and re-usage of objects by providing a trustworthy physical and digital tracking medium. For example, companies could be able to share or rent construction equipment based on a project's needs and be sure about the location, usage history, and need for maintenance without the need of human intervention.

Prolong life through maintenance, design for durability and upgradability

Along the same lines of the previous sub-area, extending a product's life becomes feasible when it is considered from one of the first steps in the Product Life Cycle (PLC) – the design phase. Although not a technology *per se*, planning since the design phase how to extend a product's life might be an essential enabler for creating circular systems (Zeiss et al., 2021; Interview C1; Interview A1).

When looking at the consumer electronics industry, one of the most plastic and metal demanding, Andrae et al. (2016) introduce the benefits of taking sustainability-driven decisions since the design phase. According to the authors, the logic is that when a company focuses on designing the next generation of electronic products with the employment of 'greener' materials and manufacturing processes in mind, they usually come with efficiency gains which in turn result in larger economic benefits. In this same industry, the systematic review's oldest included article, Dalrymple et al. (2007), talks about the rising issue of Waste from Electrical and Electronic Equipment (WEEE) *even before* the explosive growth of the mobile phone industry. The increasing amounts of plastic types used in the manufacturing of electrical and electronic devices, as well as the incompatibility between the individual classes of polymers used, are presented as barriers for recyclability that could be minimised through a design-for-sustainability approach and be further improved with the use of AI technologies (Interview C1).

On a related topic, the advantages that designing for recyclability brings to a company also apply to other industries. For the food packaging industry, it could mean a closer adherence to market pressures for using recycling or compostable materials in the disposable packaging used (Clark, Trimingham & Storer, 2019; Interview C1). Moreover, by limiting the total amount of materials used in a set of products, companies in the furniture industry could achieve both higher efficiency and circularity levels, as detailed by the B3 interview participant.

However, prolonging the life of products represents a direct measure against the consumerism lifestyle that has been fostered for the last century. Hence, regulatory measures such as the one taken by the French government in terms of making the reparability of electronic and electrical devices a mandatory aspect (Yeung, 2021) will hopefully result in companies implementing sustainability-oriented design processes.

4.2.3 Optimise

The ‘Optimise’ action area concentrates on the increase of efficiency through performance or waste reduction of products as well as on the leverage of technologies to maximise production processes and outputs (EMF, 2015). Thus, this action area is one of the most impacted by the emerging technologies, and it encompasses the sub-areas to be discussed next.

Increase performance / efficiency of product

Increasing the efficiency and performance of products by investing in new technologies is usually something that appeals to companies due to the more straightforward demonstration of investment returns (Kouhizadeh, Zhu & Sarkis, 2020). Currently, when reviewing the performance of final plastic products, a common strategy to improve its functioning is to design and create a new type of polymer that performs according to the requirements. However, this strategy does not align with the production of biopolymers as it would make them difficult to recycle and would defeat the purpose of producing bio-based plastics.

Here is where the field of *synthetic biology* also becomes relevant. In the ‘Regenerate’ action area, the *feasibility* of producing *bioplastics* is discussed. This subsection relates to the *improvement* of the properties of biopolymers and bioplastics through the use of synthetic biology techniques. On this matter, the food industry presents optimistic scenarios where *bioplastics* are improved by conferring antimicrobial properties, also from organic sources, to food packaging (Milovanovic et al., 2018). Moreover, by adding biopolymer-based nanocomposites to the technology mix, an extension of shelf life of fruits and vegetables (Fierascu et al., 2019; Laibach, Börner & Bröring, 2019; Interview C1) or the improvement of physical properties of *biopolymers* (Basumatary et al., 2020) is becoming an increasingly viable option.

Remove waste in production and supply chain + Leverage big data, automation, remote sensing, and steering

The reason for introducing digital technologies in supply chains is to "create a single integrated ecosystem able to harmonize and manage the planning of purchases, production, stocks, distribution and services, with the final aim to guarantee a high quality of products and services to the end customer." (Braglia et al., 2021, p.195). So, either in combination or from a standalone perspective, authors in the systematic review highlight several emerging technologies that reduce waste (Clark, Trimingham & Storer, 2019), enable the closure of resource flows, and create value while reducing costs and increasing revenues (Ranta, Aarikka-Stenroos & Väisänen, 2021). Thus, taking into account this conjunction of objectives, this sub-area blends the two remaining units within the 'Optimise' action area as indicated in its title.

An auspicious combination of technologies that could mean a considerable leap forward in terms of efficiency in the production and supply chain is made up of *Big Data*, *Artificial Intelligence* (AI) through its various branches (e.g. machine learning, computer vision, automation capabilities), and the *Internet of Things* (IoT) (Pagoropoulos, Pigosso & McAloone, 2017; Vrchota et al., 2020). Although this might sound complicated from a manufacturing perspective, the mechanism is quite simple from a systemic standpoint: *AI* provides the logic and the processing of data that is supplied in real-time by the *IoT* sensors or based on the historical performance (*Big Data*). This mix becomes even more interesting when adding *autonomous robots* into it as it extends the AI's capabilities by giving it control over the manufacturing devices so that continuous monitoring and optimisation of performance and processes can be achieved (Acioli, Scavarda & Reis, 2021; Braglia et al., 2021). Sovacool et al. (2021) present a scenario where this technology assortment can be translated into 'precision agriculture' techniques that determine the exact fertiliser quantities needed per crop and field, resulting in economic (less product needed), social (less added chemicals in consumer products), and environmental (less GHG emissions) efficiencies. Furthermore, the C1 interviewee highlights the capabilities of this technology set to make waste sorting more efficient and, thus, more profitable.

Another technological mix with great potential is known as *Process Intensification (PI)*. This efficiency-driven strategy employs chemical engineering and process optimisation techniques to accomplish a cleaner and more efficient use of the resources involved in the manufacturing steps (Boffito & Fernandez Rivas, 2020; Sovacool et al., 2021). In other words, *PI* delivers resource efficiency and waste reduction by "maximizing mass, heat, and momentum transfer" (Boffito & Fernandez Rivas, 2020, p.2502) in production processes. The reach and impact of *PI* can be amplified when combined with other emerging technologies such as *additive manufacturing* (Acioli, Scavarda & Reis, 2021) to create custom-made pieces that enable *PI* plant layouts on the physical grounds, with *AI* technologies for real-time process optimisation and decision-making, with *carbon capture and storage technologies* (CCS) to reduce GHG emissions since the productive stages, or with organic synthesis microreactors that translate production processes from batch to continuous (Boffito & Fernandez Rivas, 2020). PI techniques are already being applied in a practical setting, as described by the B1 interviewee. In spite of these advantages, the lack of success stories, the operations-oriented legacy systems in supply chains, and the perceived scalability issues are some of the barriers that *PI* encounters in a practical setting (Boffito & Fernandez Rivas, 2020).

Lastly, a couple of authors put forward the mix of *Big Data Analysis* and *Cloud Computing*. According to Braglia et al. (2021), the small and medium businesses that constitute an important portion of the Italian fashion industry could greatly benefit by collaboratively implementing these technologies at an industry-wide scale to obtain improved production capacity forecasts and consumer trends. Ranta, Aarikka-Stenroos & Väisänen (2021) also detail the use of this technology mix to process large datasets that aim to generate more accurate forecasts on both the supply and demand grounds of the refined chemicals industry.

Notwithstanding, when looking at these technologies independently, appealing advantages are also present. The benefits of using *IoT* technologies for tracking unique items (Pagoropoulos, Pigosso & McAloone, 2017; Gligoric et al., 2019), and management of e-waste and agricultural waste (Nižetić et al., 2019) are already available without the need of complex data processing tools (i.e. AI and Big Data). Even more, data collection through this type of technologies, Ranta, Aarikka-Stenroos & Väisänen (2021) mention, helps organisations capture incremental value from the tightening of resource flows via cost savings; however, integrating and analysing this data would enable larger gains from these technologies.

4.2.4 Loop

The 'Loop' action area entails the necessary processes and technologies that *close the loop* and aim to reintroduce materials back into the system either through remanufacturing, recycling, or extracting valuable matter from waste (EMF, 2015). Within the plastic materials value chain, this action area shows the most significant number of technologies that enable a circular economy, and it is divided as follows.

Remanufacturing of products or components

The remanufacturing of products is an important inner loop within the CE model since it extends the life of components and thus lowers the associated manufacturing emissions along the product's life cycle. Considering the durability and composition specificity of the plastic materials used in certain industries (e.g. automotive and electronics), one would think that remanufacturing processes play an essential role. However, this is not the case, and only one article in the systematic review showcased a technology applicable to this sub-area. Pagoropoulos, Pigosso & McAloone (2017) present the use of *Radio Frequency Identification* (RFID) tags to track product and material flows to enable value recovery through what they call 'Re-strategies' (p.21) such as reuse, repair, and remanufacture. Following this logic, the technologies used in the 'Share' action area could also be applicable to allow remanufacturing.

Derived from the systematic review literature and the interviews, the main reason behind this apparent lack of technological focus in the remanufacturing loop relates to a lack of infrastructure that enables ‘reverse logistics’ for the gathering of products amid the End-of-Life (EoL) stage either in the form of mono-plastic waste stream (e.g. only PVC plastics) (Dalrymple et al., 2007; Interview P1) or from a general plastic waste perspective (Clark, Trimingham & Storer, 2019; Vollmer et al., 2020; Interview B3).

Recycle materials

Recycling materials is not a new concept, but it is still one of the most important in transitioning to a CE model in the plastic materials value chain. Emerging technologies, needs, and barriers aligned to this sub-area were identified in the systematic review and the expert interviews.

Blockchain technology is highly relevant in this topic due to its two main functionalities: transparency/traceability and security/reliability/immutability (Kouhizadeh, Zhu & Sarkis, 2020; Zeiss et al., 2021). On the one hand, the transparency and inherent traceability of materials along the entire value chain provide the needed visibility of an end-product’s material composition and therefore, allows the recycling entities to know if and how a product is to be recycled (Dijkstra, van Beukering & Brouwer, 2021; Interview C1; Interview P1). For example, the ability to know the polymer composition, provenance, and the number of times a specific plastic package (Dalrymple et al., 2007) or clothing item (Kazancoglu et al., 2020) has been recycled are two use cases showcased in the review. On the other hand, the security, reliability, and data immutability of a decentralised network allows for greater degrees of trust between the different entities involved in the value chain (Böckel, Nuzum & Weissbrod, 2021). This, in turn, results in better communication and collaboration that not only lower the operational issues of recycling (Hussain, Mishra & Vanacore, 2020) but also improve the transport and logistic systems throughout a product’s delivery stages (Bag et al., 2021).

Saberi et al. (2019) elaborate on the barriers encountered by this technology, detailing that its adoption in the supply chain affects the stakeholders involved from both the internal (employees) and external (partners) perspectives. Technology immaturity being a significant obstacle for the technology’s adoption, they add up, which is an insight also shared by some of the interviewed experts (Interview P1; Interview P2). Additionally, other significant barriers are put forward by several authors. A lack of management vision and workforce obsolescence (Bag et al., 2021), as well as technical understanding of the technology’s capabilities (Böckel, Nuzum & Weissbrod, 2021), stand out as internal hindrances of blockchain’s exploitation for CE purposes. From the external standpoint, the openness for cooperation and collaboration due to cultural differences (Bag et al., 2021) or to a lack of systems interoperability (Kouhizadeh, Zhu & Sarkis, 2020) are also found in literature and the practical perspective (Interview P1; Interview S1). Besides, the reliability of information entered into the blockchain (Howson, 2020) and the need for validation and certification by external entities (Böckel, Nuzum & Weissbrod, 2021) are barriers additionally shared by the S1 interviewee.

Similarly to the ‘Optimise’ action area, the most transformative effect occurs when several technologies are combined to perform complementary functions throughout several steps in the value chain. Adding use cases to the ones presented in the previous subsection, a technological system where *AI*, *IoT*, and *autonomous robots* technologies work together could provide the needed capabilities to disassemble products and sort waste feedstocks in order to facilitate plastic recycling processes (Bauwens, Hekkert & Kirchherr, 2020; Interview C1; Interview A1). However, the thrilling part of the 'Loop' action area is that Information Technologies (IT) are relegated to a secondary role in the following two sets of technologies that showcase the largest potential for transforming the plastic materials value chain: 'Chemical recycling' and 'Biorefineries'.

Recycling plastic waste is challenging mainly due to four reasons (Hahladakis & Iacovidou, 2018; Hsu, Domenech & McDowall, 2021; Interview C1; Interview P1; Interview A1). First, every polymer family (e.g. PET, PP, PVC, PS) has different physical properties, so different recycling techniques are needed to process them. Second, there is a massive and constantly growing quantity of plastic compounds that are designed without taking recyclability into consideration. Third, final products are rarely made out of a single material and therefore, recycling processes, even if adequate for a single plastic type, might not work for products made out of several materials (e.g. wood, metal, etc.) or plastic types. And fourth, even if a plastic does manage to be recycled, it can be recycled so many times because, with every cycle, its properties degrade until a point when it cannot be recycled anymore. Traditionally, the recycling of plastic waste has been done through mechanical procedures which, although they are still in a growth phase and provide a viable alternative for some plastic types and waste streams (e.g. PET bottles recycling), they are unable to process all types of plastic waste for the reasons detailed above (Interview A1). This results in the majority of plastic waste to be either sent to landfills (Verma et al., 2016; Interview C1; Interview P1), incinerated to produce highly polluting energy (Gradus et al., 2017; Interview C1; Interview P1), or dropped into the ocean (Jambeck et al., 2015), with all the environmental concerns that these outcomes entail.

The set of technologies and processes encompassed within the *chemical recycling* umbrella term aim to address these challenges by breaking the polymer's chemical bonds and convert them back to a monomer state where it can be processed again as if it came from a virgin source (Vollmer et al., 2020; Interview P1; Interview S1). Although this technology is still in an early stage, it promises the ability to process different types of plastic waste streams without the loss of physical properties, and thus, it is presented as a viable alternative to reintroduce used plastic into the production system (Interview P1; Interview A1; Interview S1). The review presented by Vollmer et al. (2020) details several chemical recycling techniques like pyrolysis, solvolysis, gasification, and dissolution/precipitation that are further enhanced by chemical procedures such as microwave heating, plasma reactors, or supercritical fluids usage. Jing et al. (2021) exhibit favourable results for the usage of compound chemicals (Ru/Nb_2O_5) in the recycling process of arenes plastics. Bauwens, Hekkert & Kirchherr (2020), and Erickson et al. (2021) also talk about these technologies' benefits and future development paths.

Nonetheless, chemical recycling also faces significant challenges. Technical and economic feasibility barriers to scale are found in the literature (Vollmer et al., 2020; Jing et al., 2021) and mentioned by experts A1 and P1. Technology readiness (Dijkstra, van Beukering & Brouwer, 2021) causing a slowdown in its adoption (Interview P1; Interview P2) and the low quality of resulting plastic for the fabrication of textiles (Hussain et al., 2021) or other products (Interview P1; Interview S1) are also mentioned. The large amounts of energy used in the process, as well as a misconception regarding the applicability of this technology to all types of plastics, are also mentioned by A1 and P2 interviewees.

Finally, albeit more importantly, several authors (Dijkstra, van Beukering & Brouwer, 2021; Vollmer et al., 2020; Interview A1) agree that while chemical recycling plays an important role, it does not necessarily solve the plastic waste problem, as it patches the issue rather than tackling the problem at the root. Even more, it might be the case that it discourages the expansion of other, more effective CE loops, such as reuse or share (Dalrymple et al., 2007; Interview C1) or even cannibalises on the currently more efficient mechanical recycling methods (Interview A1).

Lastly, a remarkable and disruptive concept that aims to tackle the main issues of WEEE recycling, but one that can also be applied to other industries, is put forward by Sahajwalla & Hossain (2020). The central idea of *microrecycling* is to use a distributive recycling approach to avoid the technical and financial barriers faced by the processes and companies involved in the scaling of materials recycling. This means that, instead of having a centralised waste management system, the processing and reintroduction of valuable materials into the system happens at a smaller scale through 'microfactories' – providing new life to previously difficult-to-process waste while producing added-value materials at a local level.

Digest anaerobically + Extract biochemicals from organic waste

A *biorefinery* is a processing facility that utilises several technologies and equipment to convert biomass into products such as fuel, chemicals, energy, and other materials (Pinales-Márquez et al., 2021). In other words, it is the "renewable equivalent of a fossil-based (petroleum) refinery." (De Buck, Polanska & Van Impe, 2020, p.2). Figure 17 illustrates the material flow throughout the biorefinery concept. Within the processes used to transform the biomass that commonly comes from industrial and household waste streams, both anaerobic digestion and the extraction of biochemicals are part of the biorefinery concept. For this reason, the two remaining sub-areas of the 'Loop' section are merged into one.

Several articles emphasise the role that *biorefineries* could exert on the plastic materials value chain (Eseyin, Steele & Pittman, 2015; Satchatippavarn et al., 2016; Puyol et al., 2017; Fermoso et al., 2018; Gontard et al., 2018; Fierascu et al., 2019; Laibach, Börner & Bröring, 2019; Massaya et al., 2019; Tian et al., 2019; Pinales-Márquez et al., 2021). Considering that one of the main outputs of *biorefineries* is biopolymers, that is, plastic materials made out of organic sources or *bioplastics*, the effect that this concept brings cannot be overstated. In essence, it signifies the end of the over-dependence on fossil fuels to fabricate this ubiquitous material and a huge step towards a bio-based, closed-loop economy. To understand the impact, a brief description of how biorefineries work and the technologies involved is put forward.

First, as its primary feedstock, biorefineries typically employ biowaste (lignocellulosic biomass or 'green waste') that could be derived from a variety of sources, such as agricultural waste (Morone, Tartiu & Falcone, 2015; Fermoso et al., 2018; Tian et al., 2019) industrial or point-of-sale waste like spent coffee grounds (Massaya et al., 2019; Interview B1; Interview P1), or household waste (Arun et al., 2020; Interview P1). The use of wastewater as a feedstock source has received attention as well (Puyol et al., 2017). Further on, from a general and simplified perspective, biorefineries process biomass primarily through three stages where biochemical, thermochemical, and biological methods are involved: pretreatment, conversion, and downstream processing (De Buck, Polanska & Van Impe, 2020).

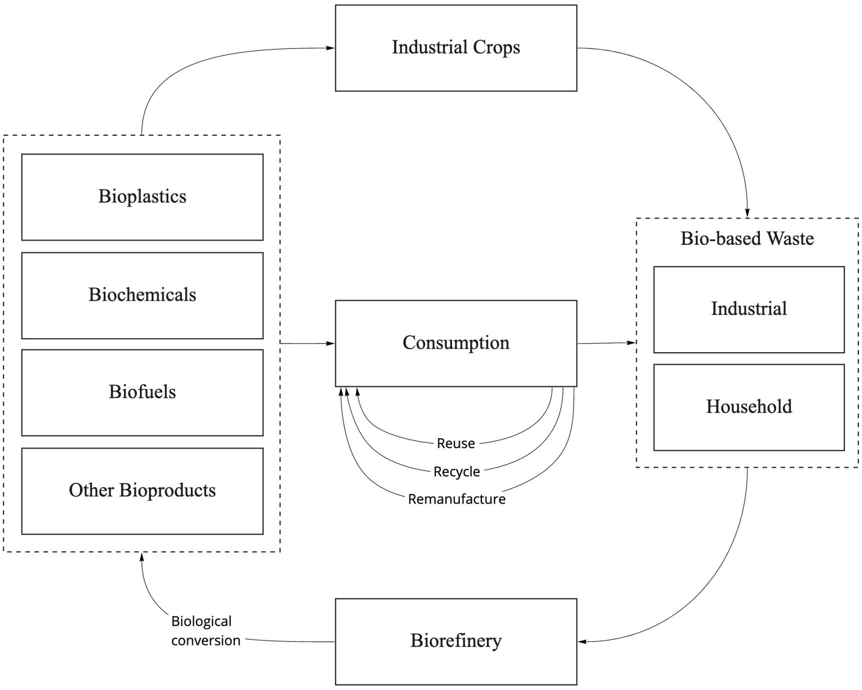


Figure 17. Circular Economy and Biorefineries.
Own diagram based on Pinales-Márquez et al. (2021).

During the pretreatment step, processes in line with the ones used in mechanical (e.g. milling) or *chemical recycling* (e.g. pyrolysis, gasification) of plastic are used to break down the feedstock matter into more basic and manageable elements used in the next stage. On the conversion stage, techniques such as anaerobic digestion (Puyol et al., 2017; Fermoso et al., 2018; Gontard et al., 2018; Bauwens, Hekkert & Kirchherr, 2020) or torrefaction (Eseyin, Steele & Pittman, 2015), among several others (Gontard et al., 2018), are used to process the biomass. The extraction of biochemicals occurs in the last step, downstream processing, where the output includes several types of biopolymers (Arun et al., 2020; Interview C1) as well as a great diversity of biochemical compounds. Complementarily, upstream processing, where the extraction of biochemicals and production of biopolymers happens before the anaerobic digestion phase, is also an effective and feasible strategy (Gontard et al., 2018). Regardless of the order of these steps, a key aspect of the three processing steps is that the use of enzymes and other genetically-modified organisms is the rule rather than the exception. So the same set of technologies mixing chemistry and biology (i.e. synthetic biology) that are enlisted on the ‘Regenerate’ action area also are applicable and widely used on biorefineries.

Furthermore, Puyol et al. (2017) state that both in refineries and wastewater treatment, polymers are only one of the outputs. The production of biohydrogen (Nižetić et al., 2019; Tian et al., 2019), other biogases (Hussain, Mishra & Vanacore, 2020), and diverse biofuels (Gontard et al., 2018) from biomass are already being used at an industrial scale with B1 confirming this. Luo et al. (2016) elaborate on the methods to produce refined glycerol and other added-value chemicals from crude glycerol, a byproduct from biodiesel's production. Active food ingredients such as xylooligosaccharides (XOs - Pinales-Márquez et al., 2021) and a great variety of antioxidants (Fierascu et al., 2019) can also be obtained through this method. The fact that *biorefineries* are designed to process and deliver various products (bioplastics, bioenergy, biofuels, biochemicals) from diverse waste streams (industrial and household waste, as well as wastewater) in a sustainable manner is key to support the economic viability of the *biorefinery model* (Satchatippavarn et al., 2016; Fermoso et al., 2018; Vollmer et al., 2020).

Regarding the barriers that *biorefineries* confront, the availability and continuous supply of feedstock (Fermoso et al., 2018; Massaya et al., 2019), the technical and economic scaling (Satchatippavarn et al., 2016; Fermoso et al., 2018; Mukherjee et al., 2019; Arun et al., 2020; Hussain, Mishra & Vanacore, 2020), a lack of organisational alignment and value perception towards the utilisation of waste (Satchatippavarn et al., 2016; Hussain, Mishra & Vanacore, 2020), and current market dynamics regarding the competition between actors and materials involved (Morone, Tartiu & Falcone, 2015; Satchatippavarn et al., 2016; Mukherjee et al., 2019) stand as the most important ones.

4.2.5 Virtualise

The 'Virtualise' action area relates to the direct or indirect substitution of resources by delivering utility virtually (EMF, 2015). Although a crucial action area on other grounds, regarding the topic of this thesis, this is the action area that has less impact. For this reason, the two sub-areas that constitute this action area are merged into one.

Dematerialise directly or indirectly

Two technologies can be associated with this theme according to the systematic review: *blockchain* and *Augmented/Virtual reality*.

Through its smart contracts feature, *blockchain* offers the possibility to virtualise and automate the practicalities that the legal departments of any company go through (Kouhizadeh, Zhu & Sarkis, 2020). According to the authors, this functionality will, once governments accept it, substitute the physical printed contract and all the activities related to its signing (e.g. paper usage, delivery, mobility for individuals to sign, storage of physical copies). More importantly, the auto-execution of these contracts enables the communication between machines which could mean substantial improvements from an efficiency standpoint. The downside of this scenario is that the amount of energy needed to operate the network and validate the contracts might play against this technology, essentially neutralising the environmentally-related advantages.

The employment of *Augmented Reality (AR)* or *Virtual Reality (VR)* technologies to *simulate* a real-life production facility or process before building/implementing it (Braglia et al., 2021). Together with *Big Data* analytics, the authors state, higher efficiency levels can be achieved in the long run when using these technologies that are most commonly associated with the marketing or entertainment domains. Another application mentioned by interview B1 is the use of AR/VR in the machinery training of new employees, which translates to improvements in efficiency and a potential decrease in resource waste due to machine malfunctioning or lack of timely maintenance.

4.2.6 Exchange

The ‘Exchange’ action area comprehends the shift towards replacing legacy ways of production and consumption through the use of more advanced non-renewable materials, the application of new technologies, and the choice of new products or services (EMF, 2015).

Replace old with advanced non-renewable materials

Plastic materials have been under constant improvement since they first appeared. As detailed in the ‘Loop’ action area, new applications and requirements drive the development of new compounds and types of polymers, which is precisely one of the problems that make them so difficult to recycle. Nonetheless, innovative technologies are being used to extend the life and improve the performance of both non-recyclable and recyclable plastics.

The use of *nanotechnologies* to improve the performance of plastic materials is showcased in several articles (Basumatary et al., 2020; Nilsen-Nygaard et al., 2021), following the idea of adding new functions to existing materials rather than replacing fossil-based materials (Laibach, Börner & Bröring, 2019). Moreover, Wu & Montalvo’s (2021) paper talks about the enhancement of concrete when combining it with non-recyclable plastic as a way to avoid dumping them into landfills.

Apply new technologies

The potential of *3D printing*, also called *additive manufacturing*, is worth discussing. Birtchnell & Urry (2013), Garmulewicz et al. (2018), and Unruh (2018) are strong advocates of the impact that this technology could bring with the mainstream consumer and industrial adoption of 3D printers. The authors envision virtualisation of the entire plastic supply chain, from transport logistics to production and retail, with the increased adoption and advancement of this technology by “closing the loop at a local level of scale by matching local waste sources with demand from 3D printing” (Garmulewicz et al., 2018, p.114).

In essence, the idea discussed in the three papers is that these machines will enable final consumers to ‘print’ their own goods, based on their own specifications, using their own waste (either plastic, metal or even biowaste – Garmulewicz et al., 2018), and only relying on ‘product design’ providers who will sell and virtually deliver the software needed for the 3D printers to manufacture the product. This is what Birtchnell & Urry (2013) call ‘personal manufacturing’ (p.398). Moreover, for more complex items, the concept of ‘coproduction’ (Birtchnell & Urry, 2013, p.398) comes into play where distributed and locally-framed supply chains are presented as more efficient and environmentally conscious alternatives to the current globally entangled supply chain systems.

Unruh's (2018) analysis of *3D printing* technologies' potential also presents solid arguments by comparing it with the way nature works based on the Biosphere Rules (Unruh, 2010) principles: "Additive production in the biosphere occurs on a small scale and locally, with material recovery, decomposition, and reassembly occurring largely at the point of fabrication. An appropriately developed 3D manufacturing system can potentially mimic these attributes." (p.99). Among the main discussion points, Unruh (2018) presents 3D printing as a potentially disruptive technology for the entire plastic materials value chain by enabling the shift into a socio-technical system that focuses on a mono-material, value-cycling, and autonomous dynamics that prioritises function over form and scope over scale; the latter being a thought also shared by Sahajwalla & Hossain (2020). Interestingly, the need for a simplification or exhibited intricacy of the plastic materials value chain is also mentioned in the expert interviews B3, A1, and C1. In other words, 3D printing, if adequately developed and regulated, could work as the ideal platform for a circular economy.

Nevertheless, and similarly to most of the other transformative technologies mentioned in this thesis, several obstacles are being faced by *3D printing*. Technologies that aim to disrupt structures and networks from a systemic perspective are the ones that encounter the largest resistance, coming especially from current players. So, first and foremost, the no-risk, predictability- and profitability-driven organisational culture exerts the largest pressure to avoid change (Birtchnell & Urry, 2013; Garmulewicz et al., 2018; Unruh, 2018). This notion is also confirmed in the expert interviews (Interview C1; Interview A1) not only for this technology but for all innovations that involve deep systemic change. On a second level, the current quality of 3D-printed products (Garmulewicz et al., 2018) and market acceptance of products coming from recycled materials (Interview P1) are mentioned as important barriers.

Choose new product / service

The development, adoption, and expansion of technologies largely depend on the way humans interact with them. So, although it is a topic that falls outside the scope of this thesis, the shift towards new business models based on the rental of products rather than the purchase and later substitution plays a crucial role within the transition towards circularity. From this perspective, *blockchain* (Esmaeilian et al., 2020; Böckel, Nuzum & Weissbrod, 2021; Erickson et al., 2021; Zeiss et al., 2021), *IoT* (Gligoric et al., 2019; Acioli, Scavarda & Reis, 2021), and several other IT's (Pagoropoulos, Pigosso & McAloone, 2017; Bongomin et al., 2020; Vrchota et al., 2020; Acioli, Scavarda & Reis, 2021; Zeiss et al., 2021) facilitate the implementation of novel business models that align with CE principles along the consumption stages of the plastics value chain.

4.3 Summary of the Emerging Technologies Identified

To facilitate the understanding of this thesis' results, Table 11 exhibits a high-level summary of the emerging technologies applicable to each action area of the ReSOLVE framework.

Table 11. Summary of the Emerging Technologies Used in Different Circularity Strategies (ReSOLVE framework).

Technologies	**Regenerate**	**Share**	**Optimise**	**Loop**	**Virtualise**	**Exchange**
3D Printing			X		X	X
AR / VR					X	
AI			X	X		
Autonomous Robots				X		
Big Data			X		X	
Biopolymers	X	X	X	X		
Biorefineries				X		
Blockchain	X	X		X	X	X
Chemical Recycling	X			X		
Cloud Computing			X			
IoT			X	X		
Microrecycling				X		
Nanotechnologies			X	X		X
Process Intensification			X			
RFID				X		
Synthetic Biology	X		X	X		

5 Discussion

This section discusses the results of the research and data obtained through both methods under the MLP framework and displays the overall limitations and possible improvements of the research.

5.1 Discussion of the Results

5.1.1 The Plastic Materials Socio-Technical System

Looking back, 1907 is a moment admitted to marking the dawn of the Polymer Age (Sutton, 2020). This new material that could feasibly be produced in cheap and massive quantities meant that the limits of nature no longer constrained humans from a material perspective (Science History Institute, 2016). With time, what had been a niche innovation in an organic materials regime, successfully became a disruptive technology that would eventually transform the entire socio-technical system. In Freinkel's (2011) words: "In product after product, market after market, plastics challenged traditional materials and won, taking the place of steel in cars, paper and glass in packaging, and wood in furniture." (p.22).

Above all, plastic became the material enabler of the linear economy. As one of the main categories of the petrochemical industry, plastic's steep uprising has actively contributed to the growth of the fossil-based economic system. Furthermore, considering that the economic growth pace achieved over the last century is reciprocally connected to the growth of fossil fuels production and consumption (Lahiani et al., 2019), it becomes reasonable to assume a correlation between the expansion of the plastics industry and economic growth through a linear paradigm. This association becomes more apparent when considering the 'Take-Make-Use-Discard' model that heavily relies on plastic materials and is an example of the linear economy.

As such, the plastic materials socio-technical system shares many actors, institutions, and materiality elements with the fossil fuels and energy systems as well as with other firmly established sectors such as the agro-food, electronics, transport, or textiles, among many others. Consequently, when analysing the ongoing technical transition of the plastic realm, the CE, together with the emerging technologies that enable it, present a viable model to transform not only the plastic socio-technical system but a significant portion of the reigning production and consumption paradigm.

5.1.2 Socio-Technical Landscape

The plastic materials S-TR is subject to several external pressures shaping the speed and direction of the transition.

On the one hand, some pressures exert a positive influence on the S-TR from a sustainability standpoint. There is a widespread acknowledgement and push towards changing the current exclusively profit-driven systems into other alternatives that equally prioritise the social and environmental aspects (Raworth, 2017; Sovacool et al., 2021). The integration of digital technologies (digitalisation) in the manufacturing stages seems to make tangible changes from a practical perspective. Moreover, increased awareness and an emphatic call-to-action to address the plastic pollution issues (Interview A1) from consumers and governments is another important force in the system.

On the other hand, significant pressures that negatively influence the S-TR away from a sustainability-driven transition are also present. An increase in the use of plastic in everyday products due to, for instance, an increment in individual portion packaging for food (Clark, Trimingham & Storer, 2019; Sovacool et al., 2021), sanitary measures related to the COVID-19 pandemic (Acioli, Scavarda & Reis, 2021), or the mimicking of consumption patterns of developed economies by nations in the Global South (Interview A1) play an important role.

5.1.3 Socio-Technical Regime

From the interviews and literature reviews in this research, several characteristics of the current S-TR are revealed. First, *technological path dependency* and its underlying risk-minimisation, reward-predictability, and efficiency-maximisation attributes in terms of investment and development affect both the rate and the direction of the transition (Interview A1; Interview P1; Interview P2; Unruh, 2018; Clarke, 2019). Second, the decisions taken by key players in the system are primarily profit- and efficiency-driven (Gontard et al., 2018; Interview P1; Interview B1; Interview B2, Interview P2). Third, it is heavily reliant and interdependent on the fossil-based materials S-TR regime (Eseyin, Steele & Pittman, 2015; Mukherjee et al., 2019; Interview A1). Fourth, it is focused on the production and valorisation of single products (mono-system) while ignoring or neglecting other possible outputs (pluri-system), and so, it is wasteful (Satchatippavarn et al., 2016; Puyol et al., 2017; Gontard et al., 2018; Interview B1; Interview B2; Interview B3; Interview C1). Fifth, the plastic materials value chain is extremely complex regarding the materials, actors, and connections with other systems (Interview P1; Interview B1; Interview A1; Interview S1; Wu & Montalvo, 2021).

Technology

One of the key features of established S-TRs is that big players are reluctant to change, and the plastic materials S-TR is no exception. *Risk aversion* (Interview P1; Interview P2, Interview B2) is a defining characteristic of the current S-TR that permeates the pace, direction, and magnitude of the transition and the adoption of circularity-enabling disruptive technologies. The main reasons behind this behaviour are described next.

First, the petrochemical industry, being an asset-intensive one, means that the installed capacity in terms of machinery and processes could end up becoming obsolete (sunk investments). So, it is expected for the current actors, with massive locked-in investments, to defend their position and technologies in place (Clarke, 2019) – *"Everyone is lobbying to have some sort of an influence because they have a lot to lose. Literally a lot."* (Interview P2). Second, technology immaturity causes players in privileged positions to wait for it to develop before they decide to adopt it (Interview P2; Interview A1) – *"We like to see some success track record before we engage and start to use any new technologies."* (Interview B2). Sometimes, even though big actors are testing and pushing towards the spread of new tools that enable circularity, smaller players keep being sceptical and wait until it becomes a requirement (from their clients) or from the regulatory side to embrace novel technologies (Kouhizadeh, Zhu & Sarkis, 2020).

Third, even if a specific technology brings clear benefits in terms of efficiency or quality, in order to reduce uncertainty and risk, an industry-wide consensus is needed for the majority of actors to accept the adoption of innovative technologies (Interview S1; Hussain, Mishra & Vanacore, 2020; Erickson et al., 2021). Fourth, new technologies create new customers (Interview B1) but also new competitors (Interview P1); thus, players will seek to push for the spread of technological solutions that keep them in a position of power. For example, although a breakthrough technology and a creator of new players, chemical recycling does not fundamentally change the regime's dynamics in terms of machinery, actors, and value chain hierarchy (Interview S1; Interview P2; Interview A1; Bauwens, Hekkert & Kirchherr, 2020).

For these reasons, the development of innovative technologies is mainly in the hands of those who have less to lose and more to win – the entrepreneurial firms. These firms, who are developing the technological inventions needed to change the regime's dynamics, are cautiously brought in and pushed towards the wanted direction of larger players (Interview B2; Interview P1; Interview B1).

On a related note, the exponential growth of the plastic S-TR during the past decades also meant that companies became *extremely efficient in both quality and costs* along the entire production process of plastics (Interview P2). Therefore, it is very difficult for any solution to compete with the existing players merely on economic grounds. For example, virgin plastic packaging is the best available option for food items regarding both material properties and cost (Milovanovic et al., 2018; Clark, Trimingham & Storer, 2019), and while several other alternatives for packaging exist, their elevated production costs become prohibitive to be used on a large scale. Therefore, manufacturing companies often must decide between sustainability and efficiency in the products they fabricate and the processes they use (Interview B1; Interview P1; Interview B2) – *"Today our customers are eager to get more sustainable, more recycled materials. So the demand is definitely there. But of course, they are not willing to suddenly blow up their costs because no [final] customers today are suddenly willing to pay two, three, four times the amount of money even if they are extremely sustainable. Simply not possible."* (Interview P2).

Hence, technologies that, at least initially align with corporate dynamics (less risk and uncertainty) and achieve sufficiently high efficiency levels will be the ones to more effectively drive the transition towards a CE in the plastics value chain.

User Practices and Markets

The market demand for a shift towards sustainability-driven processes and products is one of the leading forces behind the transition that the plastic S-TR is experiencing. Increasingly, end consumers' demands (Interview B1; Interview B2; Interview C1; Interview P1; Interview S1; Interview B3; Interview P2; Andrae et al., 2016; Clarke, 2019) are driving companies in the productive stages of the plastic materials value chain to *make sustainability a priority* along the different steps of their products' life cycles.

These market exigencies require firms to exhibit deep commitments also in terms of values and purpose (Interview B1), which, depending on the company's attitude, will be seized as an opportunity – *"So it's a good investment to do it now. Because then you are there, you are in the safe side and you are leading the market of sustainable factories."* (Interview B1), or as a liability – *"There's not one elegant solution to it."* (Interview B2). The important question here is that both literature and experts interviewed acknowledge that *change is happening – "They were quite resistant in the beginning. They didn't believe that this industry would change and then you had a couple of early adapters that said 'Okay, it's fine, we'll do it for you' but now, they have realised that 'Sh*t! This is the future; no one is asking for fossil-based plastics anymore'."* (Interview S1).

As a result, high-level sustainability pledges coming from top management positions in all types and company sizes (Interview P1; Interview P2; Interview B2; Interview B3) are being presented. Nevertheless, the challenge is a significant one – *"Design for circularity: when you talk about it, it sounds relatively easy, but sometimes in practice, it's complicated."* (Interview P1). The need for developing recycled plastics that achieve the same quality and properties as the ones made from virgin plastic (Interview P1), the lack of acceptance of recycled plastics (Garmulewicz et al., 2018), and the need to prove that new technologies and processes are profitable at the company level (Interview B2; Interview C1) stand as the most significant ones.

Ergo, technologies that equip producers with the technical and marketing capabilities to showcase and sustain their sustainability achievements will be the ones to gain the most from this transition.

Culture

Every regime has an underlying cultural foundation that moulds the thinking and acting of its actors. In this thesis' case, it is acknowledged in both literature and interviews that a shift in the *perception and concept of waste* must be looked upon – *"We need to change the way people think about trash (...) The whole circular economy stands or falls the moment you have a bag of trash, and you can either make something new out of it, or you have to burn it. At this point in time, we burn most of it."* (Interview C1).

Reframing human's relationship regarding resource usage and what is considered 'waste' will play a huge role in the current sustainability transition. Puyol et al. (2017) highlight the benefits that a simple mentality shift "From water remediation to water mining" (p.2) would bring in the treatment of wastewater even without the need to use sophisticated technologies. This is a thought shared by Bauwens, Hekkert & Kirchherr (2020), who talk about the need for large behavioural changes in low-tech approaches towards circularity. Moreover, Interviewee A1 elaborates on this idea: *"So far we're still talking about plastics as a sort of pollution issue mainly. We're not really addressing the heart of really thinking about 'how do we use materials?', but rather, 'how do we get rid of the waste?'"*.

Designing out waste in production processes and product life cycles is one of the core principles of the CE model. So, technologies and companies that enable materials' re-utilisation (Interview B1; Interview B2), propel a shift away from the mono-product focus, and thus redefine the concepts of 'value' and 'waste' (Interview A1, Interview C1; Clark, Trimingham & Storer, 2019) will most likely take off in this transition.

Infrastructure

The current infrastructure of the plastics value chain is based on linear economy principles. Therefore, companies are encountering problems when looking to employ waste-based feedstocks for the solutions that are being tested – *"The more access we can get to the waste-based feedstocks, the more fossil-based feedstocks we can replace."* (Interview P1). This becomes evident when talking about how mono-plastic waste streams are an increasingly wanted feedstock type (Interview S1; Interview P1) that is essentially changing market dynamics: *"We're seeing now a sort of competition for recycled PET. In some markets of the world, we've seen that recycled PET is actually more expensive than virgin."* (Interview A1). Plastic waste management, collection, and sorting represent important barriers for technologies that work with specific materials.

Hence, firms and technologies that use more realistic, contaminated, and mixed materials waste streams (Vollmer et al., 2020; Interview P1; Interview S1) will prosper faster. Additionally, technologies that aim to address the problems related to collecting and sorting waste will face a similarly successful path.

Industry Structure

As discussed in subsection 5.1.1, the plastic materials sphere exhibits *high levels of complexity* and entanglement with related industries (Interview S1; Interview A1), which causes collaboration and alignment between stakeholders to be very challenging tasks (Interview P1). The *standardisation* of materials (Interview B3; Interview C1; Interview S1) and data structures (Interview P1; Interview S1) at the industry level appear to be two key aspects that support a transition towards a CE model. However, to achieve this, open and secure collaboration channels towards a shared goal must be created. This is where emerging technologies are presented as viable alternatives to achieve circularity.

Moreover, the *efficiency- and profit-driven rationales* that characterise the linear economy are behind every major decision taken by its actors. Thereby, companies' adoption and scaling of emerging technologies in the plastic S-TR mainly have to do with the involved cost either in time or capital (Interview B1; Interview B2, Interview P1; Interview S1). Not surprisingly, this logic also applies to the CE efforts at the firm level – *"When it comes to companies engaging in circular economy and manufacturing practice, it really does come down to cost."* (Interview B2). The good part of this argument is that efficiency not only applies to the reduction of cost but also to the better usage of other resources. This is exemplified by brands

B1 and B2 when showcasing their ambitious usage-reduction goals for water, energy, and other resources. Moreover, this logic also helps to push sustainability in companies when presenting the productivity increments of using new technologies in the production processes (Interview P2) – *"The more cheaply you can produce recycled high-quality material, the more easily the transition towards circular economy becomes."* (Interview C1).

Therefore, technologies that enable transparency and standardisation while keeping efficiency and productivity as a priority will encounter fertile grounds to flourish.

Policy

Policy performs a critical role in the transition towards a CE in the plastic S-TR. An insight shared by the literature and the interviews is that everyone is waiting to see what policymakers will do next in terms of *regulation and incentives* aimed at the plastic materials value chain. Time is a crucial aspect too, not only from the environmental need of drastically reducing carbon emissions from human activity but also regarding the current stage in the development of emerging technologies – "As 3D printing is still early in its adoption curve, now is an opportune time to consider how policy can influence its development." (Unruh, 2018, p.98). Nonetheless, regulation is a two-sided weapon. It can either impel or hinder the development of emerging technologies.

On the one hand, more stringent regulation may push companies to innovate in order to comply with the set limits. Bauwens, Hekkert & Kirchherr (2020) highlight the rapid emergence of bio-based chemicals in Germany as a result of more strict environmental regulation. Interviewee B1 also adheres to this thinking and talks about how policy-driven environmental measures are extended to other countries when a company expands overseas. Further, Interviewee P1 elaborates on this matter – *"Whenever regulation starts to prescribe that a certain percentage of plastic materials actually need to be recycled-based, is when we'll see what is really going on."*. On the other hand, less strict regulation causes companies to move slower by simply complying with the bare minimum, which, depending on their values, will strive to increase their sustainability achievements and set an industry standard (Interview B2), or fail to achieve substantial improvements (Interview C1).

The worst position, however, is when regulation ignores the issue or fails to define a technology's playground, causing a technological evolution solely based on market dynamics. For example, a lack of government support is stated as one of the main barriers to the proper development of anaerobic digestion technologies (Hussain, Mishra & Vanacore, 2020). The risk here is that, considering the linear economy dynamics of the market, the shape that technologies will take might end up not being transformative enough for the socio-technical system to actually enable the required transition.

The critical point is that there is a *need for common goals* (Clark, Trimingham & Storer, 2019; Clarke, 2019), and legislation is the primary channel to achieve this. Hence, technologies that demonstrate high transformative impact at all levels of society in the present and future, causing policymakers to include them in their political agendas, will be the ones that will achieve faster adoption rates. Even more, technologies that showcase their value and alignment with the policies currently being discussed (e.g. 'Green New Deal' or 'EU's

Taxonomy') clearly and understandably will be the ones to see a brighter future in their domain areas.

Techno-Scientific Knowledge

Collaboration is one of the aspects needed to implement a CE model at an industry-wide level successfully. This is true on several fronts via the standardisation of materials or technology protocols, as mentioned earlier, but also in the scientific and technical development of the CE-enabling technologies. From both data sources used in this thesis, the need for a *collaborative approach* to tackle the technical challenges that the emerging technologies are facing is mentioned.

Several arguments in favour of this approach for knowledge creation in various industries and technologies are found in this research: Erickson et al. (2021) for the pharmaceutical industry, Kazancoglu et al. (2020) for the textiles industry, Clarke (2019) for synthetic biology technology, and Saberi et al. (2019) for blockchain technology. Moreover, there is a latent need to research and understand the long-term effect of bioplastics in nature (Interview B2; Interview C1; Interview S1; Dijkstra, van Beukering & Brouwer, 2021), a task that, without true collaboration, will be impossible to be carried on by a single actor regardless of its size or position in the value chain. However, the current S-TR does not reward or incentivise collaborative practices, as highlighted by Kazancoglu et al. (2020) in the case of blockchain, or detailed by interviewee C1 from a general perspective: *"Everybody is trying to reinvent the wheel instead of collaborating. It's logical, but inefficient."*.

In the end, a shared pursuit in terms of techno-scientific knowledge can be translated to an efficiency and productivity topic (Interview B1; Interview B2; Interview P1; Interview S1), and it becomes evident for players who are seeing what is happening from a high-level perspective. Accordingly, technologies that enable collaboration between different entities to achieve a shared understanding and common goals will reach greater acceptance from a scientific and industrial perspective.

5.1.4 Niche Innovations

The emerging technologies that have the largest potential to accelerate and conduct the transition towards a CE in the manufacturing stages of the plastic materials value chain are the ones that more precisely address the needs of the S-TR while using the 'windows of opportunity' created by the landscape pressures to their advantage. This research identifies four sets of emerging technologies that will act as enablers and exhibit the most considerable potential in disrupting the plastic materials S-TR: chemical recycling, biorefineries, distributed economies, and Industry 4.0 technologies.

Chemical recycling

The set of technologies behind the 'chemical recycling' term poses a promising technological avenue that will contribute to enabling a CE model within the plastic value chain. Regardless of which of the technologies encompassed in this term will turn out to be triumphant, the core idea of 'returning plastic waste to a basic monomer structure for it to be reintroduced in the system' is a powerful proposition.

Arguments in favour of this emerging technology include a positive marketing message, the re-utilisation of materials, a redefinition of the concept of waste, an industry-wide impact promise and an alignment to current political discussions. Most importantly, this technology aligns with the current corporate dynamics in terms of installed capacity for both the production of recycled plastic and the utilisation of mixed and contaminated waste. Nonetheless, at this point in time, chemical recycling techniques have not been able to demonstrate sufficiently high efficiency levels to be scaled since they consume vast amounts of energy and other resources. Moreover, they do not help change the mono-product focus dynamics and fail to foster standardisation and transparency. Above all, the diversion of attention from the inner loops of the CE model (prevention, reduction, reuse, refusal) stands as the major drawback of chemical recycling associated with the transition in question.

Biorefineries

The thought of 'fabricating value-added products from biowaste', which associates with the set of technologies (e.g. anaerobic digestion) and products (e.g. bioplastics) entailed in the biorefineries concept, seems very appealing from a sustainability transitions standpoint, almost like a panacea. Moreover, leveraging on the 'economies of scope' model, biorefineries present a viable alternative to the systemic reliance on fossil-based fuels. Nonetheless, this emerging technology represents such a profound and system-wide transformation that the resistance it may encounter could end up being counterproductive to its expansion.

On the positive side, biorefineries will provide a very positive public image for the entities that venture into this area; they enable materials' re-utilisation and fundamentally change the perception of waste and value. They also use a mixed and contaminated waste source (although not uniquely fossil-based plastic), keep efficiency and productivity as a priority by focusing on the production of several products, and are very aligned to the political discussion topics through the concept of 'bioeconomy'. On the negative side, being a direct threat to the majority of actors in the plastic material's S-TR stands as the largest barrier. Additionally, while some of the processes are already being used at an industrial scale (e.g. biofuels' production), most technologies involved are still at an infancy stage, which creates a lack of clarity on the outcomes and features of the technology stand as the main points.

Distributed economies

As opposed to the centralised and large-scale economies on top of which the linear economy stands (Johansson, Kisch & Mirata, 2005), the concept of *distributed economies* aims to shift the economic paradigm into more local (or even personal) systems of sourcing, manufacturing, consumption, and recycling. The hurdles that many disruptive solutions encounter in the scaling and expansion phases can be overthrown through a combination of emerging technologies that enable this novel concept (3D Printing/Additive Manufacturing, IoT, Blockchain, AI, and Cloud Computing). Examples of these solutions include the 'microrecycling' and 'distributive manufacturing' concepts detailed in section 4. Even more, by enabling auto-sufficiency and enclosing the production of goods into a smaller scale and geography, activities that are currently perceived as non-profitable (e.g. marine plastic waste collection) may become so.

Supporting arguments for this set of technologies include a complete redefinition of the concepts of waste and value, the re-utilisation of materials, the employment of mixed waste streams, a distributive form of addressing sorting and collection of waste, and a promise of society-wide impact. On the other hand, factors that play against this solution include a complete misalignment with corporate dynamics, high levels of conceptual ambiguousness, and, at least initially, relatively low efficiency levels.

Industry 4.0 technologies

Lastly, rather than elaborating on the role of specific emerging technologies (for this, see Section 4), the data exchange and automation capabilities enabled by Industry 4.0 technologies in the manufacturing stages of the plastic value chain exhibit great potential. This becomes a prominent part of the discussion when considering the industry's digitalisation stage – "Unlike Sustainable Development, digitalization in the chemical industry is still in its early stages." (Keller & Bette, 2020, p.10).

When analysed from a group perspective, favourable forces behind these technologies include a promise of efficiency and productivity increase, the generation of positive marketing messages towards the consumers, an enabling of materials' re-utilisation, a potential use of mixed waste sources, the enabling of transparency and collaboration among actors, and a prominent societal impact which aligns to current political discussions. Forces against the technologies' development and adoption relate to a relative misalignment to corporate dynamics since they represent risk and a failure to both shift away from a mono-product focus and redefinition of the 'waste' and 'value' concepts.

5.2 Limitations and Future Research

Besides the limitations detailed in Section 3 that relate to the methodologies employed, some limitations arise from the specific manner that this thesis is carried out. Although these areas of improvement do not mitigate the contributions of the current writing, it is important to take them into account for the interpretation of results and the definition of further research avenues. The lack of time solely stands as the main reason to conduct the research in the way that it is presented rather than fulfilling the improvements to be listed next.

First, although sufficient for the type of analysis and mix of methodologies used in this thesis, interviewing professionals that have experience in the 'Converters' and 'Monomer producers' stages of the plastic value chain could serve as a valuable complement to the obtained insights. Moreover, conducting independent thematic analyses for both methodologies could also have resulted in more detailed insights to shape the understanding of the phenomenon in question.

Second, following the suggestion of Tranfield, Denyer & Smart (2003), having more than one reviewer for the process of selecting the studies included in the systematic review is undoubtedly an opportunity for improvement. Having a peer with whom to discuss which articles to include and conjunctively decide in case of doubts supports the unbiasedness and objectivity goals of a systematic review.

Third, while expert interviews provide a deep, insightful perspective to explain the phenomenon in question, other methods such as massive surveys or the Delphi method could also deliver important information regarding the rate of adoption and future expansion paths of emerging technologies from a practical perspective.

Lastly, depending on the approach that future researchers might want to take, the usage of other sustainability transition frameworks such as the Technological Innovation System (TIS) might deliver thought-provoking results when analysing the present phenomenon.

6 Conclusion

The objective of this chapter is to respond to the study's goal and research question, as well as to highlight the investigation's major discoveries.

Merging two nascent fields of research, the purpose of this thesis is to identify and understand the role, barriers, and impact that emerging technologies have in the transition towards a circular economy model throughout the productive stages of the plastic materials value chain.

With data obtained through two separate yet complementary qualitative methods – a systematic literature review of 55 academic articles and eight expert interviews, theoretical and practical insights are jointly classified and analysed through the ReSOLVE framework. For the interpretation of these insights in terms of the 'sustainability transitions' theory, the MLP framework is employed to answer the following research question:

How can emerging technologies enable the transition towards a circular economy model along the manufacturing stages of the plastic materials value chain?

From a theoretical perspective, the results of this thesis are partially aligned with previous research. Emerging technologies more closely associated with the IT sphere (i.e. Industry 4.0) play an important role by enabling the exchange of data and automation, thus increasing efficiency and productivity through all steps of the value chain. However, in the transition towards a CE in the plastic materials realm, the lead role is taken by emerging technologies that are more aligned with the chemistry and biology disciplines, displacing the former technologies onto a supportive, yet still vital, position. In summary, based on the ReSOLVE framework action areas, 'Optimisation' is supported by IT while 'Loop' is enabled by technologies on the biochemical sphere.

From a practical standpoint, the strong bond between the linear economy model and the plastic materials world delineates the magnitude and direction of the transition. Practitioners are aware and often understand the full transformative potential of the existing technologies but are constrained by the predominantly profit-driven dynamics of the analysed socio-technical regime. Moreover, these dynamics are also determining the pace of the transition. Enormous investments in the currently installed capacity that works under the linear economy principles and industry structure run the risk of becoming obsolete faster than expected – causing the need to prolong decisions and extend the current practices for as long as possible or until an imminent shift originates from either policy or market demand. This mix of factors causes a theory-practice gap between what is envisioned by the literature and what is occurring in practice.

The four identified sets of technologies that enable circularity in the plastic materials value chain are enclosed as chemical recycling, biorefineries, distributed economies, and Industry 4.0 technologies. From different angles and varying scope, each of these technology sets operationalises the circular economy principles and represents a fundamental shift in the current modus operandi of the socio-technical regime in question.

Notwithstanding the profound systemic change required, radical transformation always meets the strongest resistance. To overcome this friction, a number of adoption pathways are put forward. Foremost, the technologies that first align to the efficiency- and profit-driven principles of the dominant linear economy and subsequently transform the dynamics from the inside, will be the prevalent ones. Likewise, technologies that exhibit the least risk in their adoption, achieve comparable efficiency levels as the current technologies, help companies in supporting their sustainability achievements, enable material's re-utilisation, redefine the concepts of 'waste' and 'value', utilise the current waste management capabilities, enable transparency and collaboration, seek standardisation, demonstrate a transformative impact, and are conceptually understandable for policymakers will have the most prominent role in the transition towards a CE.

7 References

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8 Appendix

Appendix A. Review Protocol for Systematic Literature Review.

Review Question	How can emerging technologies enable the transition towards a CE model along the manufacturing stages of the plastic materials value chain?	
Review Objectives	From the theoretical standpoint, identify the technologies and how they work, identify the needs they address, understand how they align to the CE principles, and identify the barriers that hinder their development.	
Inclusion Criteria	Is the article published in a peer-reviewed scientific journal?	
	Is the publication written in English?	
	Does the publication treat the interaction or exhibits a direct connection between emerging technologies, circular economy, and the plastics industry?	
Data Search	Scoping search performed on April 3rd, 2021, through 'briefsearch' and 'building blocks' strategies.	
	Final database queries run on April 16th, 2021 in EBSCOHost, Emerald Insight, Wiley, Scopus, and Web of Science.	
	Total articles retrieved	522
	After removing duplicates	502
	After screening	173
	After full-text review	49
	Final set of articles	55

Appendix B. Databases and Search Queries.

Database	Query string and Expanders/Limiters
EBSCO Host	**Databases:** Academic Search Complete, Business Source Complete, EconLit, GreenFILE, Library, Information Science & Technology Abstracts with Full Text
	Expanders: Also search within the full text of the articles, Apply equivalent subjects**,** **Limiters:** Scholarly (Peer Reviewed) Journals
	Query string: (("sustainability" OR "sustainability transition*" OR "sustainable transition*" OR "MLP" OR "multi level perspective" OR "regime*" OR "socio-technical")) AND (("supply chain*" OR "value chain*" OR "manufacturing" OR "manufacturing chain*")) AND (("plastic*" OR "polymer*" OR "monomer*" OR "recycler*" OR "plastic converter*")) AND (("digital technolog*" OR "emerging technolog*" OR "disruptive technolog*")) AND (("circular economy" OR "circularity"))
Emerald Insight	**Query string:** (content-type:article OR content-type:"case study" OR content-type:"earlycite article") AND (("sustainability" OR "sustainability transition*" OR "transition*" OR "sustainable" OR "sustainable transition*" OR "circularity" OR "circular economy" OR "circular") AND ("MLP" OR "multi level perspective" OR "regime*" OR "socio-technical") AND ("supply chain*" OR "value chain*" OR "manufacturing" OR "manufacturing chain*") AND ("plastic*" OR "polymer*" OR "monomer*" OR "recycler*" OR "plastic converter*") AND ("digital technolog*" OR "emerging technolog*" OR "disruptive technolog*"))
Scopus	**Query string:** ("sustainability" OR "sustainability transition*" OR "transition*" OR "sustainable" OR "sustainable transition*" OR "circularity" OR "circular economy" OR "circular") AND ("MLP" OR "multi level perspective" OR "regime*" OR "socio-technical") AND ("supply chain*" OR "value chain*" OR "manufacturing" OR "manufacturing chain*") AND ("plastic*" OR "polymer*" OR "monomer*" OR "recycler*" OR "plastic converter*") AND ("digital technolog*" OR "emerging technolog*" OR "disruptive technolog*") AND (LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))
Web of Science	**Databases:** WOS, BIOSIS, CABI, FSTA, KJD, MEDLINE, RSCI, SCIELO, ZOOREC
	Period: Auto, **Language:** Auto
	Query string: TS=("sustainability" OR "sustainability transition*" OR "transition*" OR "sustainable" OR "sustainable transition*" OR "circularity" OR "circular economy" OR "circular" OR "MLP" OR "multi level perspective" OR "regime*" OR "socio-technical") AND TS=("supply chain*" OR "value chain*" OR "manufacturing" OR "manufacturing chain*") AND TS=("plastic*" OR "polymer*" OR "monomer*" OR "recycler*" OR "plastic converter*") AND TS=("digital technolog*" OR "emerging technolog*" OR "disruptive technolog*")
Wiley	**Applied filters:** Journals
	Query string: "sustainability transition" OR "circular economy" OR "sustainability transitions" OR "multi level perspective" OR "MLP" "digital technology" OR "emerging technology" OR "disruptive technology" OR "digital technologies" OR "emerging technologies" OR "disruptive technologies" “plastic” OR “plastics” "supply chain" OR "value chain"

Appendix C. Data-extraction Form.

Category	**Criteria**	**Answer options**
Bibliographic Information	Title	Text field
	Authors	Text field
	Publication	Text field
	Year	Text field
	Country of authors	More than one country, USA, UK, India, China, Denmark, Sweden, Germany, Switzerland, Other
	Link	Text field
Research Information	Industry	Agro-Food, Textile, Plastic, Electronics, Chemicals, Energy, No specific industry, Other
	Location of study	Asia, Europe, America, Oceania, Africa, Global, No specific location, Other
	Methodology	Systematic review, Review, Interviews, Case study, Article, Survey, Other
RQ	Emerging technologies	Blockchain, Waste-to-X, Bioplastics, Nanotechnologies, AI / Machine Learning, AR / VR, Process Intensification, 3D Printing / Additive manufacturing, Chemical Recycling, IoT, Big Data, Cloud computing, Other
	Needs addressed / Technology Features	Efficiency, Transparency, Productivity, Waste reduction, Brand image, Compliance (Regulation), Feasibility, Performance, Measurement, Other
	Stages of the value chain being transformed	Feedstock producer, Polymer producer, Converter, Brand / OEM, Retailer, Consumer, Waste management, Recycling, All, Other
	Main ReSOLVE action area being fulfilled	Regenerate, Share, Optimise, Loop, Virtualise, Exchange
	Other ReSOLVE action areas being fulfilled	Regenerate, Share, Optimise, Loop, Virtualise, Exchange
	How is the regime currently shaped?	Text field
	How is the regime reconfigured?	Text field
	What are the challenges or barriers for the technology in question to properly develop?	Text field
Other	Additional notes	Text field

Appendix D. Interview Guide.

Introduction (5 - 10 minutes)

- Personal introduction
- Formalities confirmation
    - Interview being recorded and transcribed
    - Confidentiality and privacy regarding the recording and transcription
    - Anonymous participation
- Brief description of the research project and its objectives
    - Understand the role of emerging technologies in the transition from linear to circular economy in the plastics value chain
    - Understand how these technologies are changing the industry and company dynamics
    - Presentation of estimated final output: map of emerging technologies and their alignment to the circular economy principles as well as the plastic value chain manufacturing stages
- Setting a common ground for key topics
    - Circular Economy
    - Plastic value chain
    - Emerging technologies

Part 1 - About the interviewee (5 minutes)

- Professional presentation
    - Company
    - Job position
    - Main activities and roles
    - Years in the industry and position

Part 2 - Identification of technologies and contribution to circularity (10 - 15 minutes)

Questions

1. Which emerging technologies that enable a circular economy does your company use?
    a. In which part of the manufacturing process?

2. How are these technologies contributing to the enabling of circularity in the plastic manufacturing stages? What issues or needs are they addressing?
    a. At the company and value chain levels
    b. Advantages, disadvantages?

<u>Part 3 - Understanding the transition and its barriers</u> (10 - 15 minutes)

Questions

3. How are these technologies changing the current dynamics of the plastics value chain?
    a. Are they only changing processes or technological systems?
    b. Or also the business dynamics in terms of competitors, consumers, government?
    c. Market preferences and players, culture, regulation,

4. What are the key challenges or barriers that hinder the development of these technologies?

<u>Closure</u> (5 minutes)

- Final comments
- “Thank you for your insights”

Appendix E. List of Included Articles with Journal and Knowledge Field.

#	Authors	Journal	Discipline
1	Acioli, Scavarda & Reis (2021)	International Journal of Productivity and Performance Management	Performance Management
2	Andrae et al. (2016)	Challenges	Other
3	Arun et al. (2020)	Industrial Crops & Products	Biotechnology
4	Bag et al. (2018)	Benchmarking: An International Journal	Organisational Management
5	Bag et al. (2021)	Journal of Global Operations and Strategic Sourcing	Manufacturing & Production
6	Basumatary et al. (2020)	Critical Reviews in Food Science and Nutrition	Food Science
7	Bauwens, Hekkert & Kirchherr (2020)	Ecological Economics	Ecological Economics
8	Bezama et al. (2019)	Sustainability	Sustainability
9	Birtchnell & Urry (2013)	Mobilities	Transportation
10	Böckel, Nuzum & Weissbrod (2021)	Sustainable Production and Consumption	Sustainability
11	Boffito & Fernandez Rivas (2020)	The Canadian Journal of Chemical Engineering	Chemical Engineering
12	Bongomin et al. (2020)	Journal of Engineering	Engineering
13	Braglia et al. (2021)	Journal of Fashion Marketing and Management: An International Journal	Marketing
14	Clark, Trimingham & Storer (2019)	Packaging Technology and Science	Packaging Technology
15	Clarke (2019)	Engineering Biology	Biology
16	Dalrymple et al. (2007)	Circuit World	Electronics
17	Dijkstra, van Beukering & Brouwer (2021)	Marine Pollution Bulletin	Marine Environment
18	Erickson et al. (2021)	Biotechnology and Bioengineering	Biotechnology
19	Eseyin, Steele & Pittman (2015)	Bioresources	Biotechnology
20	Esmaeilian et al. (2020)	Resources, Conservation & Recycling	Sustainability
21	Fermoso et al. (2018)	Journal of Agricultural and Food Chemistry	Chemistry and Biochemistry

22	Fierascu et al. (2019)	Molecules	Chemistry
23	Garmulewicz et al. (2018)	California Management Review	Management
24	Gligoric et al. (2019)	Sensors	Technology
25	Gontard et al. (2018)	Critical Reviews in Environmental Science and Technology	Environmental Sciences
26	Howson (2020)	Marine Policy	Policy
27	Hussain, Mishra & Vanacore (2020)	Proceedings of the Estonian Academy of Sciences	Other
28	Hussain et al. (2021)	Journal of Enterprise Information Management	Information Technologies
29	Jing et al. (2021)	Angewandte Chemie	Chemistry
30	Kazancoglu et al. (2020)	Sustainable Development	Sustainability
31	Keller & Bette (2020)	Journal of Business Chemistry	Chemistry
32	Kouhizadeh, Zhu & Sarkis (2020)	Production Planning & Control	Operations Management
33	Laibach, Börner & Bröring (2019)	Technology in Society	Social Sciences
34	Luo et al. (2016)	Bioresource Technology	Environmental Engineering
35	Massaya et al. (2019)	Food and Bioproducts Processing	Chemical Engineering
36	Milovanovic et al. (2018)	Food Research International	Food Science
37	Morone, Tartiu & Falcone (2015)	Journal of Cleaner Production	Environmental Sciences
38	Mukherjee et al. (2019)	Biosystems Engineering	Biological Engineering
39	Nilsen-Nygaard et al. (2021)	Comprehensive Reviews in Food Science and Food Safety	Food Science
40	Nižetić et al. (2019)	Journal of Cleaner Production	Environmental Sciences
41	Pagoropoulos, Pigosso & McAloone (2017)	Procedia	Social Sciences
42	Pinales-Márquez et al. (2021)	Industrial Crops & Products	Biotechnology
43	Puyol et al. (2017)	Frontiers in Microbiology	Biology
44	Ranta, Aarikka-Stenroos & Väisänen (2021)	Resources, Conservation & Recycling	Sustainability
45	Saberi et al. (2019)	International Journal of Production and Research	Manufacturing & Production

46	Sahajwalla & Hossain (2020)	Materials Today Sustainability	Materials Science
47	Satchatippavarn et al. (2016)	Chemical Engineering Research and Design	Chemical Engineering
48	Sovacool et al. (2021)	Renewable and Sustainable Energy Reviews	Energy
49	Tian et al. (2019)	Applied Energy	Energy
50	Unruh (2018)	California Management Review	Management
51	Vollmer et al. (2020)	Angewandte Chemie	Chemistry
52	Vrchota et al. (2020)	Sustainability	Sustainability
53	Wu & Montalvo (2021)	Journal of Cleaner Production	Environmental Sciences
54	Zeiss et al. (2021)	Information Systems Journal	Information Technologies
55	Žnidaršič-Plazl (2021)	Acta Chimica Slovenica	Chemistry

Appendix F. Top 100 Terms per Category of Interviewees.

Number in parenthesis indicates the number of mentions of that specific term.

Position	All	Brands	Producers	Others
1	plastic (174)	think (69)	recycling (38)	plastics (119)
2	think (174)	company (58)	technology (37)	recycling (112)
3	need (168)	product (50)	need (35)	need (90)
4	recycling (158)	materials (44)	plastic (33)	think (75)
5	materials (126)	need (43)	chemical (30)	sort (73)
6	technology (117)	process (35)	think (30)	material (68)
7	product (105)	time (30)	companies (28)	technology (51)
8	company (97)	waste (30)	time (26)	new (41)
9	waste (89)	technologies (29)	products (23)	waste (40)
10	sort (80)	packaging (29)	industry (22)	industry (38)
11	times (74)	water (28)	oil (21)	produce (38)
12	process (67)	sustainability (28)	waste (19)	trash (35)
13	produce (66)	produce (24)	end (19)	parts (33)
14	new (65)	end (24)	feedstocks (18)	products (32)
15	industry (64)	people (23)	emerging (17)	circular (30)
16	chemical (61)	plastic (22)	sustainability (17)	types (29)
17	sustainability (60)	agenda (20)	route (15)	economy (29)
18	parts (57)	design (19)	focus (14)	consumers (28)
19	packaging (56)	suppliers (19)	materials (14)	chemical (27)
20	people (51)	manufacturing (19)	value (14)	packaging (26)

21	circular (50)	part (18)	customers (12)	processes (25)
22	end (50)	new (18)	chain (12)	change (19)
23	consumers (45)	factories (17)	solution (12)	separate (19)
24	economy (39)	customer (14)	change (12)	time (18)
25	change (38)	develop (14)	fossil (12)	solution (18)
26	design (38)	cost (14)	believe (11)	virgin (18)
27	solutions (37)	future (13)	people (11)	people (17)
28	types (37)	consumers (13)	bio (10)	problem (17)
29	trash (36)	department (12)	money (10)	compost (16)
30	water (34)	reuse (11)	performance (10)	polyester (16)
31	focus (33)	requirements (11)	mix (10)	burning (16)
32	oil (33)	continue (11)	cost (10)	organic (15)
33	development (32)	circular (11)	streams (9)	development (15)
34	suppliers (32)	less (10)	circular (9)	less (15)
35	value (31)	market (10)	properties (9)	sustainable (15)
36	customer (30)	goal (10)	replace (8)	markets (15)
37	chain (28)	machines (10)	scale (8)	design (15)
38	emerging (28)	projects (10)	types (8)	bottles (15)
39	less (28)	buying (9)	standards (8)	transition (14)
40	cost (27)	management (9)	suppliers (8)	reusing (14)
41	markets (27)	resources (9)	data (8)	plants (14)
42	problems (26)	team (9)	grades (7)	demand (13)
43	feedstock (25)	understand (9)	players (7)	focus (13)

44	reusing (25)	recycling (8)	process (7)	bio (13)
45	bio (24)	values (8)	system (7)	blockchain (12)
46	virgin (23)	foam (8)	assets (7)	brand (12)
47	factories (23)	question (8)	efficient (7)	investments (12)
48	manager (22)	building (7)	blockchain (7)	pets (12)
49	organizations (22)	meet (7)	fact (7)	company (11)
50	separate (22)	emerging (7)	mechanical (7)	difficult (11)
51	polyester (21)	heat (7)	plants (7)	europe (11)
52	connected (21)	innovation (7)	regulations (7)	fiber (11)
53	demand (21)	problem (7)	sounds (7)	chain (11)
54	investments (21)	solutions (7)	risk (7)	manage (10)
55	manufacturing (21)	change (7)	majority (6)	contracts (10)
56	plants (21)	footprint (7)	understand (6)	content (10)
57	agenda (20)	connect (7)	cars (6)	energy (10)
58	blockchain (20)	driving (7)	cracker (6)	green (10)
59	compost (20)	organic (7)	easy (6)	oil (10)
60	systems (20)	standard (7)	economy (6)	seen (10)
61	energy (19)	complex (6)	new (6)	global (9)
62	money (19)	facing (6)	part (6)	responsibility (9)
63	buying (19)	liter (6)	suddenly (6)	value (9)
64	projects (19)	bar (6)	investing (6)	connection (9)
65	standards (19)	bigger (6)	disrupt (6)	municipality (9)
66	burning (18)	challenge (6)	economics (6)	stream (9)

67	difficult (18)	feedstock (6)	access (5)	systems (9)
68	stream (18)	support (6)	barrier (5)	past (9)
69	transition (18)	took (6)	biomass (5)	pyrolysis (9)
70	future (17)	adopting (6)	building (5)	aware (8)
71	believe (17)	decide (6)	difficult (5)	bag (8)
72	bottles (17)	efficient (6)	easier (5)	expensive (8)
73	fibers (17)	focus (6)	energy (5)	quality (8)
74	fossil (17)	responsibility (6)	particular (5)	supply (8)
75	mix (17)	demand (6)	perspective (5)	currently (8)
76	understand (17)	depends (6)	portfolio (5)	grade (8)
77	expensive (16)	pay (6)	balance (5)	issue (8)
78	responsible (16)	price (6)	feed (5)	textile (8)
79	brands (15)	realize (6)	innovation (5)	allows (7)
80	buildings (15)	across (5)	block (5)	defining (7)
81	data (15)	chain (5)	comparable (5)	enable (7)
82	efficient (15)	equipment (5)	connect (5)	end (7)
83	global (15)	involved (5)	explain (5)	firms (7)
84	grades (15)	job (5)	increasing (5)	processor (7)
85	limits (15)	keep (5)	limitations (5)	pure (7)
86	route (15)	money (5)	monomers (5)	source (7)
87	aware (14)	perspective (5)	projects (5)	test (7)
88	continuous (14)	polyester (5)	actively (4)	higher (7)
89	currently (14)	traceability (5)	additives (4)	inside (7)

90	department (14)	track (5)	buy (4)	largest (7)
91	pet (14)	batch (5)	collaboration (4)	meat (7)
92	question (14)	directly (5)	consumer (4)	transparency (7)
93	best (13)	generate (5)	exchanging (4)	verify (7)
94	contracts (13)	growing (5)	expensive (4)	advanced (6)
95	goal (13)	number (5)	issue (4)	almost (6)
96	ideas (13)	sort (5)	polymer (4)	audit (6)
97	issue (13)	textiles (5)	premiums (4)	best (6)
98	keep (13)	category (5)	produce (4)	biodegradable (6)
99	perspective (13)	ingredients (5)	startup (4)	buying (6)
100	pyrolysis (13)	profit (5)	across (4)	collecting (6)