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Faculty of Business Economics

Master of Management

Master's thesis

Life cycle analysis in a circular economy: a systematic literature study

Thimo Paumen

Thesis presented in fulfillment of the requirements for the degree of Master of Management, specialization Strategy and Innovation Management

SUPERVISOR :
Prof. dr. Stephan BRUNS

MENTOR :
De heer Luca CAMPION

2020
2021

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Disclaimer: Covid-19 crisis

This master thesis was written during the COVID-19 crisis in 2020-2021. This global health crisis might have had an impact on the (writing) process, the research activities and the research results that are at the basis of this thesis.

Preface

Before you lies the systematic map "life cycle analysis in a circular economy". It has been written to fulfil the graduation requirements of the master of management, strategy and innovation management at the University of Hasselt. I was engaged in researching and writing this masters dissertation from September 2020 to June 2021.

This masters dissertation was not my first preference, but after some research I got to know the topic better and I saw a lot of opportunities to write about. After all I'm happy that the topic chose me. This systematic map is intended for researchers that are looking for more information about life cycle assessments like how other studies have performed their life cycle assessment or what the possibilities are to take the biowaste into account. This is an important methodology in Europe's ambition to move to a more circular economy. A circular economy is an economy with the goal to re-use or recycle products repeatedly.

My research question was formulated with my supervisor, Campion Luca. Fortunately, he was always available and willing to answer all of my queries, as the research was difficult. But, conducting this extensive analysis has allowed me to answer the research question together with the secondary questions. For all of his guidance and availability during my process, I wish to thank Luca.

To all of my fellow colleagues of the master of management: I would like to thank you as well for these two educational, but strange years. We did something no one has ever done before: Graduating during a pandemic! We learned to adapt rapidly, we did complete projects and assignments digitally with group members on the other side of the globe. I never lost my interest, as there was always something worth striving for. I wish you all the best in your future career. I really hope you enjoy reading my master thesis.

Thimo Paumen

Abstract

Introduction This master thesis presents a systematic map of life cycle assessments (LCA) with biowaste as an input. An LCA is a method that helps researchers to better understand and address environmental impacts associated with certain products (ISO14044, 2006). A systematic map is an overview of the distribution and abundance of evidence in relation to versatile elements of a broad question (K. L. James, Randall, & Haddaway, 2016). The scope of this thesis is limited to biomaterials as they are one of the five key priority area in the European action plan for "closing the loop" (Philippidis, Bartelings, & Smeets, 2018). The research question of my master thesis is as follows: *How are LCAs with biowaste as an input conducted in the literature?* This question is divided into two secondary questions. *What are the limitations discussed in studies that conduct LCAs with biowaste as an input?* This question will focus on the problems one can encounter. What are the most common problems and how do other studies handle these problems (Finnveden, 2000)? *How do LCAs with biowaste as an input take previous life cycles into account?* There are multiple options for researchers to take the previous life cycle into account. This question focusses on how other studies have tackled this and what allocation method they used when only including parts of previous life cycles.

Methods The methods are fixed in a protocol, meaning that everything I do is pre-specified and cannot be changed. The screening is carried out in two stages. First, relevant articles are selected based on an analysis of the title and the abstract. Secondly, included articles enter the final stage, where they are assessed based on the full text. After multiple search strings were designed and tested, the final one returned 34 articles. Sixteen of these articles met the inclusion criteria: (1) The article is written in English, (2) the article includes an LCA, (3) the article considers the use of waste biomaterials as an input.

Results In the first question, the goal is to provide an overview of the possible limitations of life cycle assessments that are discussed in the selected articles. All of the limitations can be divided into three categories. This makes it easier to distinguish the different limitations and more straightforward for the reader to follow. The three categories that encountered the most limitations are: (i) scope, (ii) inventory, and (iii) novelty.

i. The scope of the research, including system boundaries

The scope of the research includes the level of detail. This is the depth and breadth of studies which can differ considerably depending on the goal. Studies can have different scopes, meaning that one study may leave out impacts or processes that another study has included.

ii. The inventory analysis phase

This is the second stage of the LCA and consists of input and output data with regard to the system being studied. It involves identifying all resources used to manufacture the product under study.

iii. The novelty of the product

A last limitation that was often discussed is the novelty of products. Sometimes this novelty results in high usage costs and therefore not many companies are willing to work with it. The lack of

adoption of these novel products results in insufficient data to perform a LCA. In my systematic map, I found that categories (i) and (ii) are most common as these are limitations that concern every study. Especially when comparing LCAs, the scope and inventory can lead to confusing results. Some studies have a very narrow scope as others take more than ten impact assessments into account. The third category only impacts studies with more recent products. Some products are relatively immature and as a result these are more expensive. The bio-based counterpart of plastic bottles for example is two to three times higher in price. Because not many companies choose this greener alternative, there isn't many data to rely on.

The second question focusses on providing an overview of the end-of-life modelling approaches the articles used. The aim of an end-of-life modelling approach is to represent how the (bio)waste of previous life cycles has been taken into account. In my systematic map there were two end-of-life modelling approaches that could be distinguished: The cut-off approach and the end-of-life recycling approach. The fundamental philosophy of the cut-off approach is that primary production of materials is always assigned to the primary user of a material. When a material is recycled, the primary producer does not receive credit for supplying any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary materials bear only the impacts of the recycling processes (Ecoinvent, 2021). In the end-of-life recycling approach (EOLR), the material recovery is explicitly modelled instead of being cut off. In particular, the recovered quantity of a material is typically assumed to directly replace an equivalent amount of primary material. In essence, this recycling reduces the need for primary material production and the environmental burdens linked to the use of primary material can be prevented. Hence, these prevented impacts are credited to the primary product as negative impacts (Anders Nordelof, 2019). Out of the 16 included articles, three used the cut-off approach to determine the life cycle assessments results and 13 relied on the end-of-life recycling approach. There are different reasons to determine the end-of-life modelling approach. A first reason is the difficulties in setting the cut-off point. Many used products contain recyclable and non-recyclable materials. Some of them move to further treatment such as incineration or disposal and some of them can be recycled into new materials. A second reason why researchers opt for certain end-of-life modelling approaches is the type of recycling loop the product is in. In closed loop recycling, recovered material is recirculated back into the same product system. In open loop recycling, the recycled materials will be used to develop a different product.

Conclusion To conclude, there are numerous ways studies can or cannot take the waste from previous life cycles into account. With regard to the first research question, I found that there are multiple limitations researches need to take into account. The scope of the research as well as the inventory analysis phase can have big impacts on the goal of the study. For that reason it is necessary to clearly state the goal of the research and adjust the scope accordingly. The novelty of the product studied can impact the inventory analysis phase. Lack of data is the biggest threat for this phase. Concerning the second sub question, I discovered that the end-of-life modelling approach can have a significant impact on the eco-friendliness of a product. In the cut-off approach, a product made from recycled material bears no impact of the primary product, while in the end-of-life recycling approach, the primary product is rewarded for providing recyclable materials to a new life cycle. As a consequence, some of the burdens of the primary product are transferred to the new product and are calculated as negative impacts for the primary product.

1. Table of contents

2. Introduction

Every year, over 2,5 billion tonnes of waste are generated in Europe, and this is expected to grow further in the coming years (European Parliament, 2018). In 2020, the European Union presented a new circular economy action plan as part of the European Green Deal (European Parliament, 2020). The purpose of this new action plan is to boost the efficient use of resources by moving to a circular economy and to restore biodiversity and cut pollution (European Commission, 2020a).

One of the aims of the action plan is to "close the loop" of product life cycles through greater recycling and re-use of products which will reduce waste to a minimum (European Commission, 2020b). This is also known as a circular economy: an economy where most, if not all products and materials are recycled or re-used repeatedly. Kirchherr, Reike & Hekkert (2017) define a circular economy as *"an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates 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, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers"* (Kirchherr, Reike, & Hekkert, 2017). Circular economy emerged from the traditional, linear economic model, also called Cradle-to-Grave (Ellen MacArthur Foundation, 2013). This model covers the acquisition of raw materials, production, use, and final disposal. The circular economy model is described as Cradle-to-Cradle. In this variation the final disposal stage is exchanged by a recycling process (Figure 1). Therefore, the waste material becomes reusable, closing the cycle (Liebsch, 2019). These reusable materials are also known as secondary raw materials: materials that have been recycled from waste and are replaced on the market to be used in new products (European Commission, 2015).

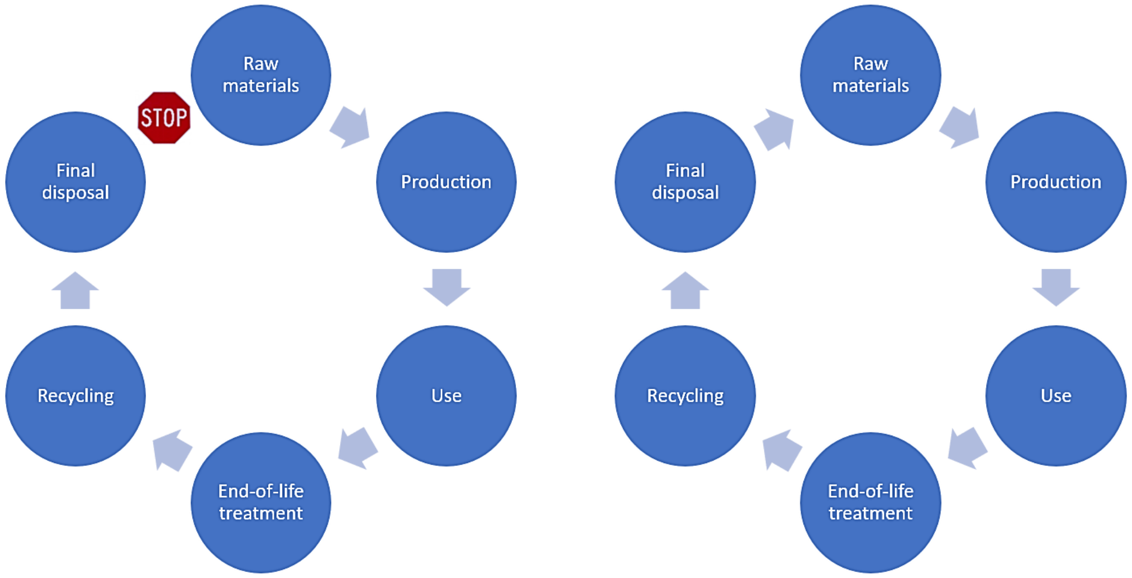

Figure 1: Cradle-to-Grave on the left compared to Cradle-to-Cradle on the right. (European Parliament, 2018)

In the shift from a linear economy with non-renewable resources to a circular economy agenda, biomaterials play a crucial role. Biomaterials are part of the natural biological cycle, which is regenerative and without any waste. The use of biomaterials is thus viewed as contributing to the circular economy in context of the innovation policy of the European economy action plan (European Environment Agency, 2018).The ambition of this innovation policy is to become more open for innovation and science. There are six important sectors in which barriers need to be lower to bring new products or services on the market. Bio-based products are one of these six sectors (Philippidis et al., 2018). The European Commission defines a bio-based economy as an economy that "*integrates the full range of natural and renewable biological resources - land and sea resources, biodiversity and biological materials (plant, animal and microbial), through to the processing and the consumption of these bio-resources. The bio-economy encompasses the agriculture, forestry, fisheries, food and biotechnology sectors, as well as a wide range of industrial sectors , ranging from the production of energy and chemicals to building and transport*" (European Commission, 2011).

Besides the circular economy action plan of the European Commission, the importance of environmental protection and the possible impacts associated with products, has raised the interest in the development of methods to better understand and address these impacts (Cerulli-Harms et al., 2018). One of those methods is life cycle assessment (LCA). The International Organization for Standardization (ISO) defines LCA as *"the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO14044, 2006).* In other words, LCA tries to give an answer to the question: what is the environmental impact throughout a specific product's life cycle?

The ISO has also provided a framework to conduct an LCA. This framework consists of 4 stages: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO14044, 2006). The first stage includes the system barrier and level of detail, which depends on the topic and the intended use of the study. This stage is important because the breadth and depth of the LCA can differ noticeably. Some LCA studies might limit their scope to assess impacts on just one environmental problem e.g. climate change. Other LCAs aim to assess impacts more broadly, including threats to human health or ecosystems caused by toxic chemicals, depletion of natural resources, the use of freshwater, destruction of habitat, and more (Daniel C. Esty, 2011). Li *et al.* discuss that when setting system boundaries, researchers should be well aware of the potential consequences. Understanding the difference between a complete and a limited system is important to evaluate the trade-offs. Trade-offs include the accuracy of LCA results, the cost, time and other factors are possible trade-offs (T. Li, Zhang, Liu, Ke, & Alting, 2014). In the inventory analysis stage, the compilation and quantification of inputs and outputs for a product are described. The impact assessment stage is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts. In the last phase the findings from the previous two stages are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Combining the two trends above – circular economy and LCA – can result in some issues. From the previously mentioned definition of an LCA it is clear that it considers the entire life cycle of a product. Starting from raw material extraction and acquisition, through energy and material production and manufacturing, to use, end-of-life treatment and final disposal. This infers that an LCA is applied on only a single life cycle of a certain product. Consequently, applying an LCA to a circular life cycle with recycled products is difficult. Practitioners must decide where the study of the waste life cycle starts (Finnveden, 1999). They can make the decision to let the study start at the new raw material phase, which implies no consideration of the waste of previous product life cycles, or to take this completely into account. There is a clear difference between both decisions and this can have a tremendous impact on the findings (Finnveden, 2000). This systematic review of existing literature tries to give an overview of how this issue has been dealt with before. It will gather a set of possible solutions from literature and broadly discuss them.

3. Objectives

The main objective of this systematic map is to study the way in which life cycle assessments (LCA) can be performed in a circular economy. To keep this literature review feasible, it was decided to limit the scope of the review to biomaterials. These are chosen because of their crucial role in the shift from a linear to a circular economy: biowaste is one of the five key priority area in the European action plan for "closing the loop" (European Commission, 2020b). Therefore, this systematic literature map tries to give an answer to the following primary research question: *How are LCAs with biowaste as an input conducted in the literature?* It is divided into two secondary questions.

What are the limitations discussed in studies that conduct LCAs with biowaste as an input? This question will focus on the problems one can encounter in a life cycle assessment with biowaste as an input. What are the most common problems and how do other studies handle these problems (Finnveden, 1999)?

How do LCAs with biowaste as an input take previous life cycles into account? There are multiple ways other studies can take biowaste of previous life cycles into account. They can include the whole previous life cycle or only a part of it. Another option could be to neglect the previous life cycle. This question focusses on how other studies have tackled this and what allocation method they used when only including parts of previous life cycles.

4. Methods

The methods are based on the Collaboration for Environmental Evidence (CEE) guidelines for systematic mapping, and the reporting standards for systematic evidence syntheses (ROSES) reporting standards are adhered too.

a. Search strategy

The literature search is conducted in Scopus for articles published up to and including 2020. This database includes peer reviewed literature and content from published books. The articles are found using the search string in Table 1. I determined two synonyms for life cycle assessment and four for waste as a resource. Boolean operators “AND’’, and “OR’’ were used to combine the search terms in every possible way: “OR” meaning extra results will appear, “AND” meaning the results will diminish.

TITLE-ABS-KEY (“life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material*" OR “secondary raw material*” OR “reusable material*”) AND TITLE-ABS-KEY (bio* OR organic)	34

Table 1: Search string used to identify articles.

Originally, cradle-to-cradle analysis, cradle-to-cradle assessment and cradle-to-cradle investigation were included in the search string. However, after multiple tests in Scopus with various search strings, it was found that no combination of cradle-to-cradle had any effect on the results. Therefore, it was decided to remove these combinations from the search string. All of the search strings that were tested with corresponding results can be found in the appendix.

b. Screening

The screening is carried out in two stages. First, relevant articles are selected based on an analysis of the title and the abstract. Secondly, included articles enter the final stage, where they are assessed based on the full text. The screening is done according to the inclusion criteria discussed in the next section. The stages are presented in a flow chart in Figure 2. The number of publications that are included and excluded are recorded, and for the articles excluded based on their full text, the reasons for the exclusion are provided.

c. Inclusion criteria

A number of inclusion criteria are used to evaluate whether or not studies returned by the literature search are included in the map. These are: (1) the article is written in English, (2) the article includes an LCA, (3) the article considers on the use of waste biomaterial as an input of the product. If after screening title and abstract it is not clear whether or not to include the article, it was included for full text screening.

d. Data extraction

The following data is extracted from the selected articles: Author, year of publication, title, country in which the study was conducted, input materials, limitations or problems and the research process of the study (To what extent did the study take waste material of previous life cycles into account? How did the study calculate the environmental impact of the circular product? What problems did the study encounter?).

e. Study mapping and presentation

All of the articles are analysed thoroughly, especially the research process, limitations, and input materials. The results are presented in a systematic map and are described on the basis of a narrative synthesis of data. Tables are created to summarize these results, and figures are designed to support the results. These tables and figures make it easier for the reader to follow.

5. Results and discussion

a. Characteristics of the included studies

The search string returned a total of 34 articles, 28 of which met the inclusion criteria based on their title and abstract. Eight papers could not be accessed using the institutional subscription of Hasselt University and the remaining 20 were explored in full. A total of 16 papers met the inclusion criteria after a full text analysis and were included in the systematic map (Figure 2). A detailed table of the articles that were excluded, with the reason why, can be found in the appendices.

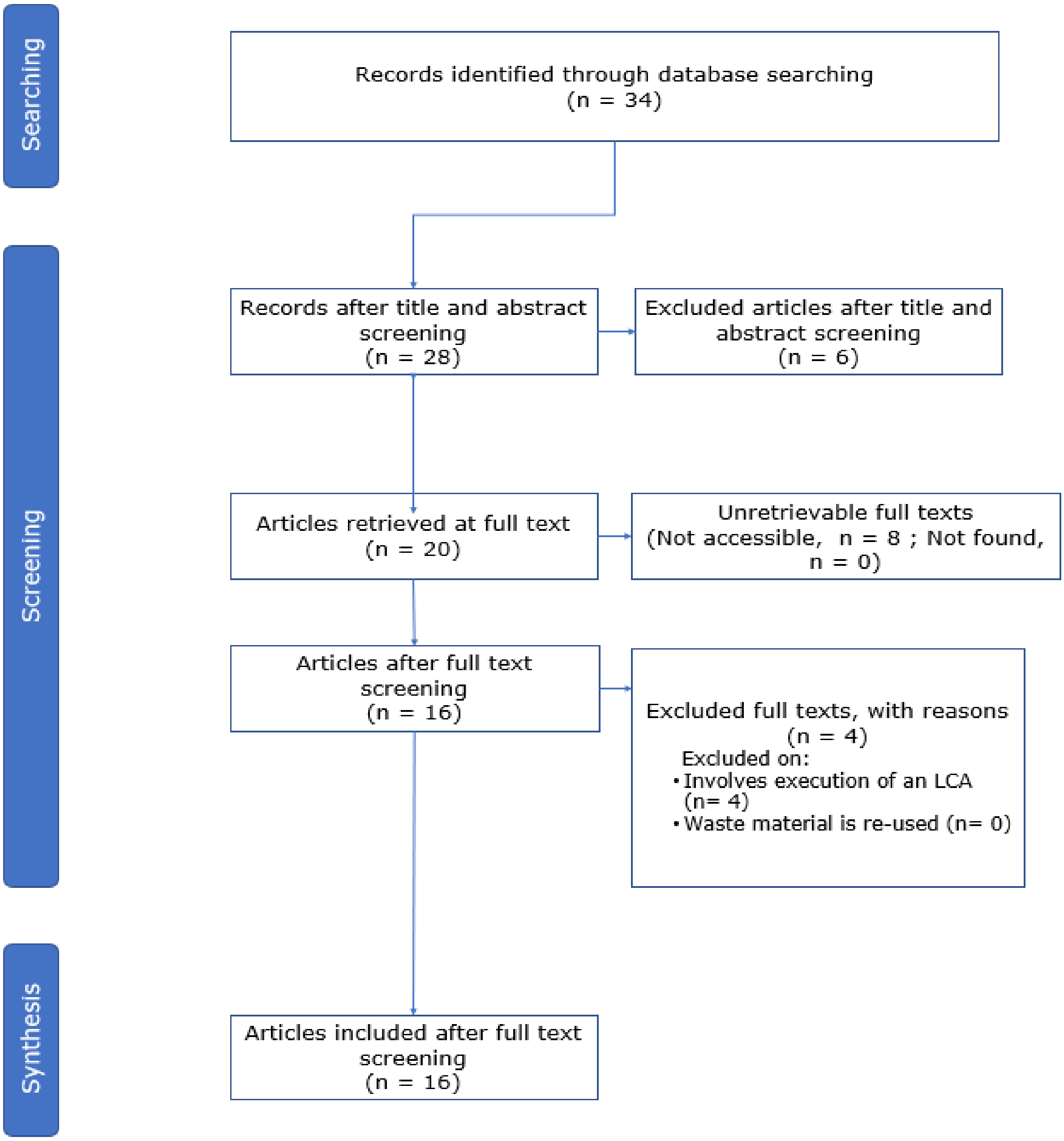

Figure 2: Flow diagram of the search strategy used, based on (Haddaway NR, 2017).

b. Geographical characteristics of the included studies

Geographically, the majority of studies were based in Europe (73,4%), Asia (13,4%), North America (6,7%) and Australia (6,7%). In terms of individual countries is Spain the overall biggest contributor to this field accounting for 20% of all studies followed by the United Kingdom and Italy (Figure 3).

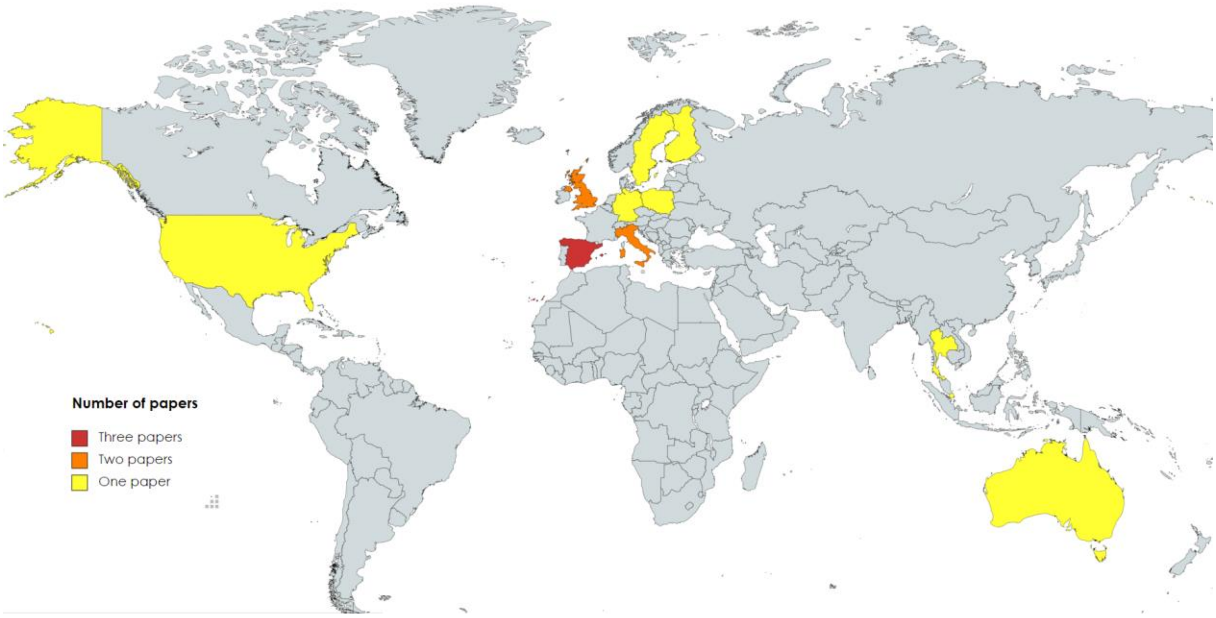

Figure 3: Map of the world showing the number of articles per country.

c. Input materials of the included studies

The input materials of all the studies are quite diverse as seen in Figure 4. The most common input materials are PET (Polyethylene terephthalate), RPET (Recycled polyethylene terephthalate) and PLA (Polylactic acid). In a second group, we find input materials like bio fibres, paper, and road or building constructing materials (RCM) like cement and concrete. Finally there was only one paper with the following input materials: Silicon wafer material (SWM) from photovoltaic cells, ashes, coffee chaff, recover cotton, recycled carbon fibres (RCF) and wood polymer composites (WPC).

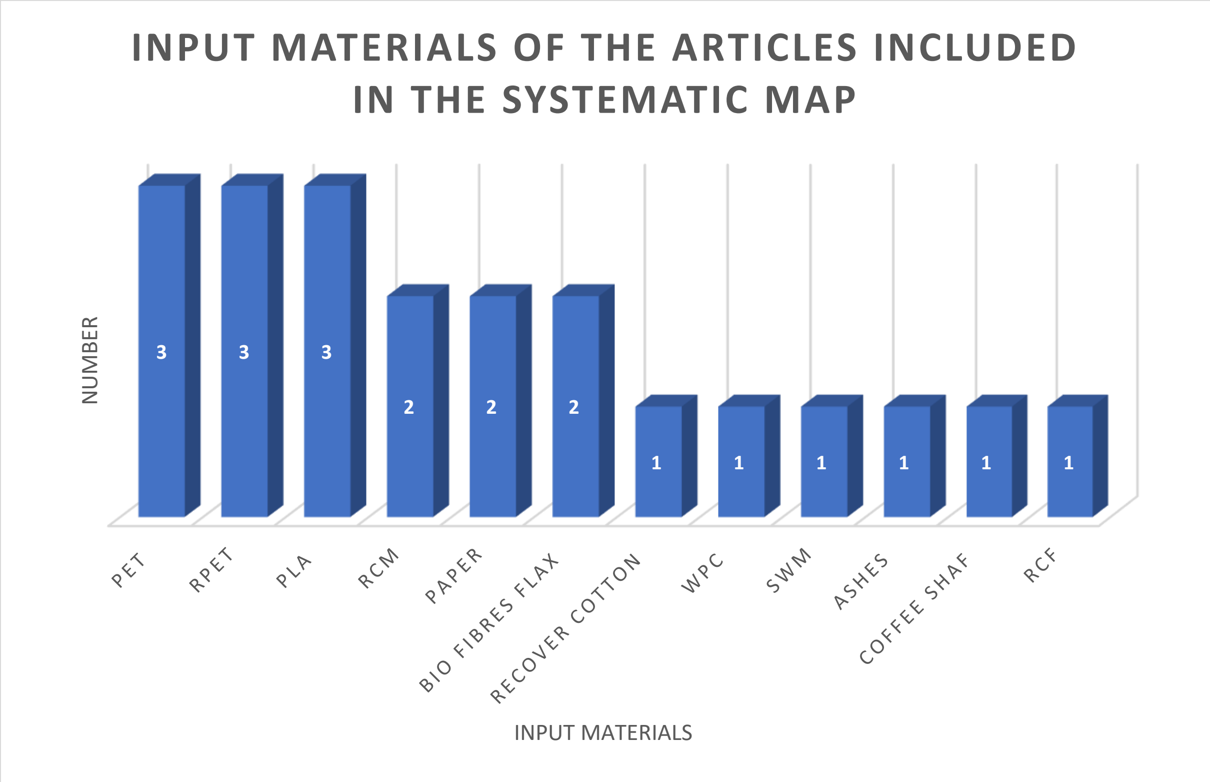

Figure 4: Graphical representation of the number of articles per input material.

d. Limits of an LCA

To answer the first sub-question (*What are the limitations discussed in studies that conduct LCAs with biowaste as an input?)*, all the limitations or problems are divided into three different categories. When a full text analysis is carried out, limitations or problems were always extracted. With the overview of all the data in mind, the decision was made to differentiate three categories of limitations. After this, each article was allocated to one of the categories. This information can be found in the last column of table 2. The categories with the most limitations are: (i) scope, (ii) inventory, and (iii) novelty.

i. The scope of the research, including the system boundaries

The scope of the research includes the level of detail. This is the depth and breadth of studies which can differ considerably depending on the goal. Studies can have different scopes, meaning that one study may leave out impacts or processes that another study has included. When choosing for less impacts, the depth of the research is way larger compared to the breath. Other studies might opt for a lot of impacts, thus choosing for more breadth. For example, some studies can include transport while others exclude transport from the LCA. This can lead to different results in the end, making it harder to compare results.

The scope of the research, including the system boundaries is a concern for every article. Each article clearly states what their scope and system boundaries are, but when comparing them there can be clear differences detected. In order to facilitate the transition to a circular economy, Rybaczewska-Blazejowska *et al.* performed an LCA of PET (polyethylene terephthalate) with its recycled and biobased counterparts RPET (Recycled PET) and PLA (polylactic acid). This LCA included 11 impact categories and therefore has a broader scope (Rybaczewska-Blazejowska & Mena-Nieto, 2020). However, in another research Välimäki *et al.* tried to find an alternative for PET in the printing process of solar cells. They did an LCA with the same input materials (PET, RPET, and PLA). The goal of their research is to find out what alternative is the most environmental friendly, but also the most practical. The scope of this research is limited to only two impact categories, meaning that they opted for a more in-depth scope rather than a broader (Välimäki et al., 2020). In 2014, Biswas W.K. *et al.* performed an LCA of constructing materials to evaluate whether or not the reuse and recovery of these materials can offer significant energy savings. The scope of the study is limited to global warming or climate change, embodied energy and transportation (Biswas, 2014). Esteve-Turrillas *et al.* conducted an LCA of recover cotton. Recover cotton is the way Esteve-Turrillas *et al.* described recycled cotton. They mentioned that they did not take into account the aspects related to the spinning of the yarn, textile production, selling and usage as well as final disposal. They broadly discuss transportation as it is taken into account (Esteve-Turrillas & de la Guardia, 2017). In conclusion, it is important to clearly state what the scope of a research is in respect to the goal. When the goal of the study is to make an LCA of the climate change, it should be discussed in depth.

ii. The inventory analysis phase

This is the second stage of the LCA and consists of input and output data with regard to the system being studied. It involves identifying all resources used to manufacture the product under study such as: processed materials, raw materials, energy, water, ... Furthermore, the choice of the impact factors is confirmed. This means that researches check if there is sufficient data available for each of the chosen impact factors. Impact factors are the wastes released into the environment like for example emission of pollutants into the air, water and soil. In this phase, researchers have a clear overview of the available data from each impact factor. With this overview in mind, the decision is finally made which impact factors to include in the study.

The inventory analysis phase is another limit of LCAs as different studies have different methods of collecting data. Esteve-turrillas *et al.* collected the data as an average of the last two years, from 2013 to 2015 (Esteve-Turrillas & de la Guardia, 2017). Proietti, S *et al.* took data from three life cycle stages in their LCA of a passive house. In the pre-utilization phase, the study relied on the ecoinvent database. In the utilization phase a lifespan of 70 years was taken into account while in the end-of-life modelling phase Proietti, S *et al.* made a clear distinction between the deconstruction and separation phase, demolition phase, and waste treatments including transportation (Proietti et al., 2013). Klugmann-Radziemska, *et al.* generated their life cycle inventory database with data from 11 European and American photovoltaic companies participating in the European Commission's Crystal Clear project. The study also relied on the ecoinvent database, however, this data all reflects European averages (Klugmann-Radziemska & Kuczyńska-Łażewska, 2020).

iii. The novelty of the product

A last limitation that was often discussed is the novelty of certain products. Sometimes this novelty results in high usage costs and therefore not many companies are willing to work with it. This is a drawback for the product itself. The lack of adoption of these novel products results in insufficient data to perform a LCA.

A last limitation is the novelty of some products. Rybaczewska-Blazejowska, *et al.* specified in their study that bio-based plastics are a relatively immature packing material, manufactured outside Europe in a limited number of facilities. As a result, the study suffered from a lack of quality foreground data (Rybaczewska-Blazejowska & Mena-Nieto, 2020). Changwichan, K *et al.* described in their study to determine the best possible material for takeaway beverage cups that bio-based plastics are fairly new, with production costs two to three times higher compared to conventional plastics. As a result, some companies may not consider the greener, bio-based alternative (Changwichan & Gheewala, 2020). The novelty of products thus leads to two problems: A first problem is the costs. Because of the newness of products these are more expensive compared to other alternatives which are maybe worse for the environment. This first problem leads to a new problem. Not many companies are willing to work with these more expensive products and as a result, there is insufficient data available. This new problem is actually a problem in the inventory analysis phase.

e. End-of-life modelling approach

Each of the 16 articles included in the systematic map applies one of two most common end-of-life modelling approaches. To give an answer to the second question (*How do LCAs with biowaste as an input take previous life cycles into account?)*, the end-of-life modelling approach is extracted from each article and included in Table 2. The aim of this, is to represent how each article has taken into account the biowaste of previous product life cycles in the performance of their LCA. This information can be found in the second to last column of table 2. The two most common end-of-life (EOL) approaches are the cut-off approach (COA) and the end-of-life recycling approach (EOLR).

The fundamental philosophy of the cut-off approach (COA) is that the primary production of materials is always assigned to the primary user of a material (figure 5). When a material is recycled, the primary producer does not receive credit for supplying any recyclable materials. This means that the primary producer does not get rewarded. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper. It is free of any burdens of the forestry activities and processing required for the primary production of the paper (Ecoinvent, 2021).

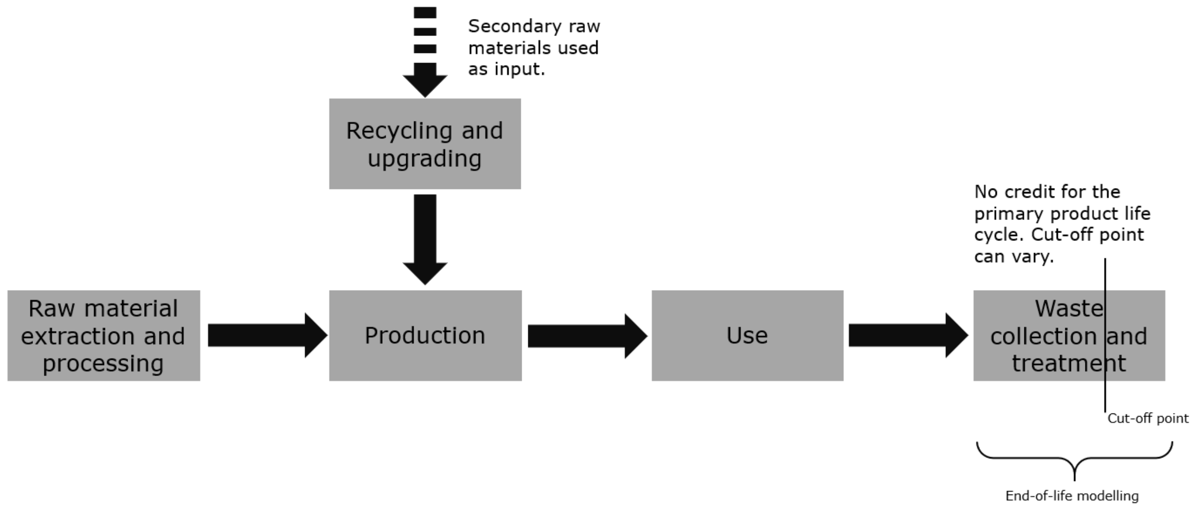

Figure 5: Graphical representation of the cut-off approach. Based on (Anders Nordelof, 2019).

In the *end-of-life recycling approach* (EOLR), the material recovery is explicitly modelled instead of being cut off. In particular, the recovered quantity of a material is typically assumed to directly replace an equivalent amount of primary material upstream in the product system, or in a different product system (Figure 6). In essence, this recycling reduces the need for primary material production and the environmental burdens linked to the use of primary material can be prevented. Hence, these prevented impacts are credited to the product studied in the EOL stage as negative impacts. A key feature of this approach, regardless of any actual recycled content of products in the real world is that: If the EOL crediting is based on avoided primary material production, then all of the materials in the downstream should also bear the load of primary material production. Otherwise, benefits of recycling are accounted for twice in the same life cycle. Imagine we look at the life cycle of paper. The virgin paper in this life cycle is obviously made from trees, so this paper bears the environmental burdens of cutting the trees, making the paper, ... After use, the paper is recycled and converted into new paper. In the EOLR approach, the virgin paper gets rewarded because it provided recyclable materials for later, new life cycles. When the new life cycle of the recycled paper starts, it takes a part of the environmental burdens of the virgin paper while the virgin paper receives these burdens as negative impacts. (Anders Nordelof, 2019).

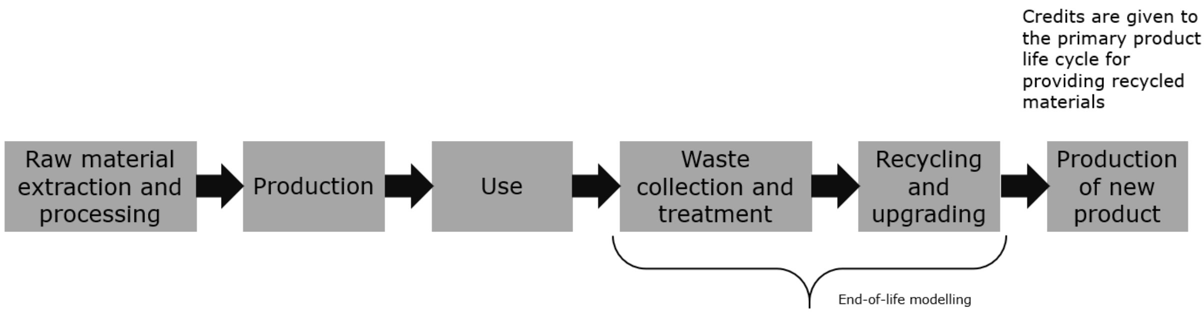

Figure 6: Graphical representation of the end-of-life recycling approach.

An overview of the *end-of-life modelling approaches* of the articles included in this systematic map are summarized in Table 2. Only 19% of the retrieved articles used the cut-off approach. Furthermore, there is no consistency in the input materials of the articles that used the cut-off approach. Changwichan, K *et al.* applied the cut-off approach in their study to determine the best possible material for takeaway beverage cups (Changwichan & Gheewala, 2020). Secondly, Ricciardi, P *et al.* adopted the cut-of approach in their research to propose coffee chaff (the dried skin of a coffee bean) as a sound insulation and absorption material for the building industry (Ricciardi, Torchia, Belloni, Lascaro, & Buratti, 2017). In the last article that used the cut-off approach, Esteve-turrillas *et al.* calculated the environmental impact of recovery cotton in the textile industry. They found that organic cotton can be more eco-friendly compared to traditional cotton cultivation. However, the organic cotton also requires a dying step which is far from being considered as a sustainable practice. Recovery cotton avoids both cultivating and dying and is therefore a good alternative. This means unsustainable practices from the other processes are cut-off(Esteve-Turrillas & de la Guardia, 2017).

All other articles worked with the *end-of-life recycling approach* as previously described. Rybaczewska-Blazejowska, M. *et al.* compared the life cycle assessments of fossil PET with its recycled (RPET) and biobased (PLA) counterparts. They found that RPET has a very good environmental profile compared to the other two, especially when taking into account the end-of-life management stages. The dominant reason for the good environmental profile of RPET is the substitution of PET and thus the avoidance of linked environmental impacts (Rybaczewska-Blazejowska & Mena-Nieto, 2020). James (2012) investigated the relationship between paper and greenhouse gas emissions from land-use change. This study found that no additional CO_2 emissions are avoided when switching from virgin to recycled paper (K. James, 2012). This indicates that he relied on the end-of-life recycling approach where the environmental burdens of the primary material are avoided.

Anders, N. *et al.* found in their research that there are different opinions in the LCA research field on where to set the cut-off point. Suggestions involve directly when the use phase has past, or after collection and transportation to a dump, where the value of the waste is the lowest. But, there is another problem when conducting an LCA with the cut-off approach. Many used products contain both recyclable and non-recyclable materials. The latter move to further treatment such as incineration or disposal. Such waste treatments are always credited to the product under study and therefore, it is recommended to model the cut-off point after sufficient separation and sorting (Anders Nordelof, 2019). For example, Zhao *et al.* Li *et al.* and Ahmadi *et al.* set the cut-off point before the separation of recyclables and non-recyclables in their research about lithium-ion batteries. This means that the incineration of non-recyclable materials is accounted for in the new product life cycle, but also in the primary product life cycle. This is in conflict with the cut-off approach as it only takes the waste from the new product life cycle into account. (Ahmadi, 2017), (Zhao, 2019), (B. G. Li, X.; Li, J.; Yuan, C., 2014). For the articles included in this systematic map, Changwichan, K *et al.* put the cut-off point before the recycling of the previous product life cycle. This means that the environmental burdens of the recycling part are considered to be part of the new product life cycle but, so is the advantage of not using virgin materials *(Changwichan & Gheewala, 2020). Ricciardi, P* *et al.* Set the cut of point after recycling in their research to recommend coffee chaff (the dried skin of a coffee bean) as a sound insulation and absorption material for the building industry. Only the burdens of transportation were taken into account in the new product life cycle (Ricciardi et al., 2017). Lastly, Esteve-turrillas *et al.* calculated the environmental impact of recovery cotton in the textile industry. They set the cut-off point after recycling meaning the new product life cycle bears no burdens of the primary life cycle (Esteve-Turrillas & de la Guardia, 2017).

Another reason why researchers choose certain end-of-life modelling approaches is determined by the recycling loop (Anders Nordelof, 2019). In closed-loop recycling, recovered material is recirculated back to the same product system (Figure 7). This means that the recovered material will develop into the same product as it was before the recycling process (ISO14044, 2006). In open-loop recycling, the recycled material is instead used in a different product (Figure 8). For the performance of LCAs, open-loop recycling has long been viewed as a challenge. The environmental burdens of the first life cycle (development, waste treatments, material recovery, ...) can be allocated in many different ways between two or more life cycles (Baumann, 2004). A couple of allocation approaches have been suggested in order to solve this issue in open-loop recycling. The cut-off approach, as described above, is the most uncomplicated and most common approach used in literature (Ekvall, 1997); (Guérin, 2017); (Baumann, 2004).

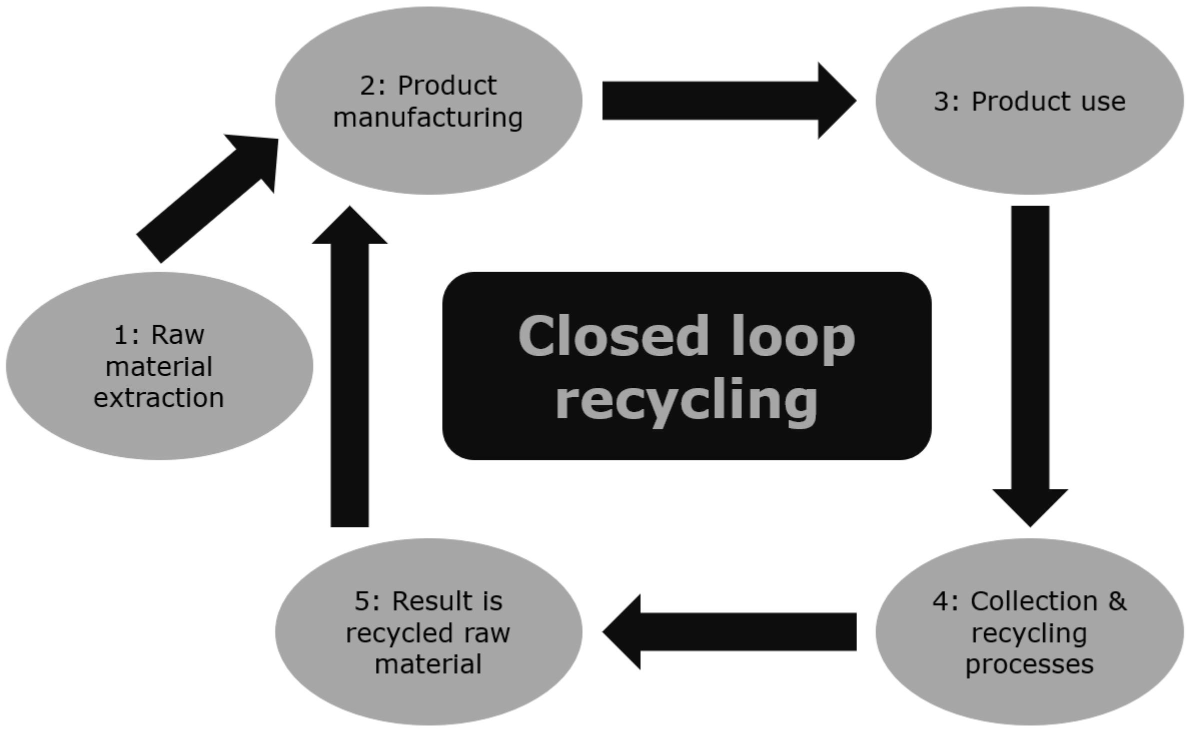

Figure 7: Graphical representation of closed-loop recycling. An example of closed loop recycling is aluminium cans. After step four, collection and recycling processes they get washed properly. The cans even skip the step of product manufacturing because they are already made. Therefore, they go directly to the use phase of their second product life cycle. Another example is PET bottles. After use and disposal by customers, the bottles go back to the company. The company then sorts the bottles according to each plastic type. In a last step, the bottles are shredded back to PET granules (small plastic particles from which the bottles are made) and the second life cycle can begin.

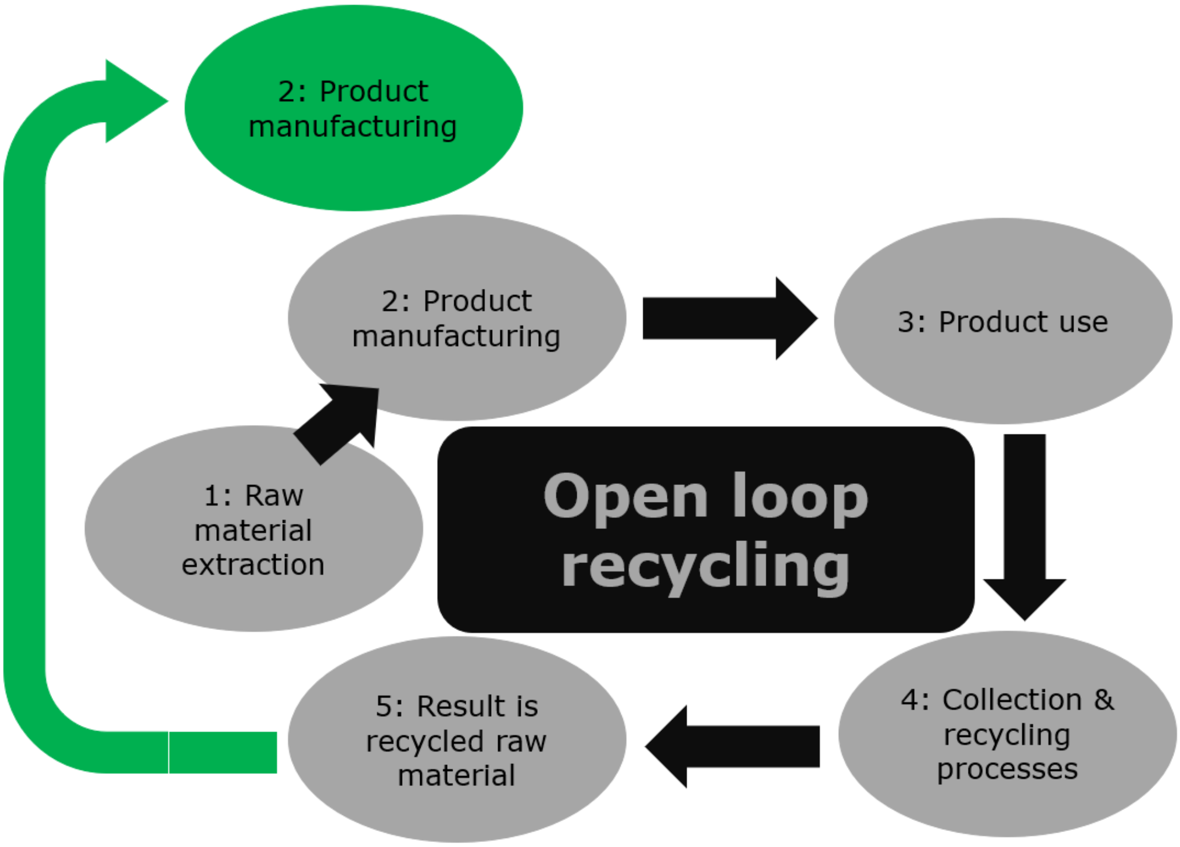

Figure 8: Graphical representation of open-loop recycling. An example of open loop recycling is, again, PET bottles. Hewlett-Packard enterprise is collecting PET bottles to be used, after recycling and other processes, in their ink cartridges (Hewlett Packard enterprise, 2020).

Table 2: The characteristics of the 16 articles included in the present systematic map investigating a life cycle analysis on bio or biobased products. Articles result from a study carried out in March and April 2021 using a combination of terms (See table 1). Abbreviations: EOLR, end of life recycling; COA, cut-off approach; 1, The scope of the research, including the system boundaries; 2, The inventory analysis phase; 3, The novelty of the product.

Nr.	Title	Author	Year	Country	Input material	End of life approach	Limits
1	Circular economy: Comparative life cycle assessment of fossil polyethylene terephthalate (PET) and its recycled and bio-based counterparts	Rybaczewska-Blazejowska, et al.	2020	Spain	PET, RPET, PLA	EOLR	1, 2, 3
2	Printed and hybrid integrated electronics using bio-based and recycled materials	Välimäki, M.K., et al.	2020	Finland	PET, RPET, PLA	EOLR	1, 2, 3
3	Choice of materials for takeaway beverage cups towards a circular economy	Changwichan, K., et al.	2020	Thailand	PP, PET, PLA	COA	1, 2, 3
4	The use of recycled semiconductor material in crystalline silicon photovoltaic modules production	Klugmann-Radziemska, et al.	2020	Poland	semiconductor silicon wafer material from photovoltaic solar cells	EOLR	1, 2
5	Environmental perspectives of recycling various combustion ashes in cement production	Yin, K., et al.	2018	Singapore	Ashes	EOLR	1, 2
6	Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review	Bachmann, J. et al.	2017	Spain	bio-fibres flax and ramie, recycled carbon fibres	EOLR	1, 2, 3
7	Environmental characterisation of coffee chaff, a new recycled material for building applications	Ricciardi, P. et al.	2017	Italy	Coffee chaff	COA	1, 2
8	Waste biorefineries: Enabling circular economies in developing countries	Nizami, A.S. et al.	2017	Developing countries	All kinds of waste	EOLR	1, 2
9	Environmental impact of Recover cotton in textile industry	Esteve-Turrillas, F.A. et al.	2017	Spain	Recover cotton	COA	1, 2
10	Wood polymer composites and their contribution to cascading utilisation	Teuber, L. et al.	2016	Germany	WPC (Wood polymer composites)	EOLR	1, 2

11	Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia	Biswas, W.K.	2014	Australia	Road constructing materials	EOLR	1, 2
12	Life Cycle Assessment of a passive house in a seismic temperate zone	Proietti, S. et al.	2013	Italy	Building materials	EOLR	1, 2
13	An investigation of the relationship between recycling paper and card and greenhouse gas emissions from land use change	James, K.	2012	UK	Paper	EOLR	1, 2
14	Comparative LCAs for curb side recycling versus either landfilling or incineration with energy recovery	Morris, J.	2005	US	curb side collection	EOLR	1, 2
15	Use of life cycle assessment to develop industrial ecologies - A case study graphics paper	Hart, A. et al.	2005	UK	Recycling systems	EOLR	1, 2
16	Evaluating a municipal waste management plan using ORWARE	Björklund, A. et al.	1999	Sweden	All kinds of waste	EOLR	1, 2

f. Software usage in the inventory stage

Another noticeable thing is the software used to conduct the life cycle assessment. Nine out of sixteen papers used the SimaPro software. SimaPro exists for over 30 years and it is a well-known tool in the industry for performing LCA's. (SimaPro, 2021). Article number 16 (Table 2) used Orware. Orware (ORganic WAste REsearch) is a simulation model and it can be used for the calculation of substance flows, environmental impacts and the costs of waste management. In this systematic map, there was only 1 article that used Orware, and the article dated from 1999.

g. Relevance

Finally, it is worth noticing that LCA is a 'hot' topic, as only 3 out of 16 papers predate 2010. This can be seen in Table 2. The number of studies has been increasing in the last couple of years. This is due to all of the new governmental regulations regarding waste like for example the European Green Deal and the two different action plans that were active in the last 6 years. Three out of 16 papers have PET, RPET, and PLA as topic as plastic waste is choking our oceans and making up 90% of marine debris. In 2016 only, the world generated 242 million tonnes of plastic, and that is just 12% of the total waste generated each year (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018).

6. Conclusion

In this thesis, I answered the following research questions. My first sub question: *What are the limitations discussed in studies that conduct LCAs with biowaste as an input?* My second sub question: *How do LCAs with biowaste as an input take previous life cycles into account?* My main research question: *How are LCAs with biowaste as an input conducted in the literature?*

With regard to my first research question, there are multiple limitations researchers need to take into account. The scope of the study as well as the inventory analysis phase can have big impacts on the goal. Especially when comparing LCA results, the scope can lead to some difficulties. Some studies can have a different or a broader scope, which makes comparing difficult. For that reason it is necessary to clearly state the goal of the research and adjust the scope accordingly. In the inventory analysis phase the intention is to confirm that there is sufficient data for each of the chosen impact categories. The collection of data and the amount of data collected can differ considerably among studies. For this reason, it is recommended to clearly state the data collection protocol details and the extend of data collection. One of the causes of a possible lack of data is the novelty of the product. In this thesis, I discovered that biobased materials are fairly new compared to their conventional counterparts. As a result of this newness, these biobased products are much more expensive. Companies still choose the more expensive, but less environmental friendly product over the expensive biobased product. When a lack of data is a threat for a study, it is better to choose less impact assessments and thus a limited scope.

With respect to the second research question, this systematic map found that the end-of-life modelling approach can have a significant impact on the eco-friendliness of a product. In the cut-off approach, a product made from recycled materials bears no impact from the primary product. The cut-off point is an important factor of this approach. In multiple studies, the cut-off point is set after the recycling stage of the previous product life cycle. To prevent that negative or positive impacts are credited twice, keeping the cut-off point in mind in really important. In contrast to the cut-off approach, the end-of-life recycling approach rewards the primary product for providing recyclable materials to a new product life cycle. As a consequence, some of the burdens of the primary product are transferred to the new product and calculated as negative impacts for the primary product.

In conclusion, this systematic map has demonstrated that it is not straightforward to conduct a life cycle assessment. Firstly, there are multiple limitations that one can encounter as described above. Secondly, there are numerous methods for each of the stages of a life cycle assessment. The emphasis of this systematic map is on the end-of-life modelling approaches as there are numerous ways studies can or cannot take waste from previous life cycles into account.

However, this study has several limitations. The emphasis is on biowaste, as this is a fairly new topic, the sample size includes 16 articles. With more and more studies on biowaste being conducted every year, this topic has large potential for future research. Further, the search string may have limited the retrieved studies. There were multiple search strings designed and teste, but it is still possible that the final one did not retrieve all the available articles. Lastly, only studies in English could be included in this systematic map.

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8. Appendices

Appendix 1: All of the search strings that were tested in Scopus.

Search string	Results
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material")	262
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation" OR "cradle-to-cradle analysis" OR "cradle-to-cradle assessment" OR "cradle-to-cradle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material")	262
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material" OR “secondary raw materials”)	320
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material" OR “secondary raw material*” OR “reusable material*”)	326
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material" OR “secondary raw material*” OR “reusable material*”) AND TITLE-ABS-KEY (bio-economy OR “bio-based economy”)	0
TITLE-ABS-KEY ("life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“bio-based product*” OR bioproduct* OR “Bio-based material*” OR “organic material*” OR “organic product*” OR biowaste)	353
TITLE-ABS-KEY (“life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material" OR “secondary raw material*” OR “reusable material*” AND TITLE-ABS-KEY (bio-economy OR “bio-based economy” OR “bio-based product*” OR bioproduct* OR “organic material*” OR “organic product*”)	2
TITLE-ABS-KEY (“life cycle analysis" OR "life cycle assessment" OR "life cycle investigation") AND TITLE-ABS-KEY (“waste as an input” OR “waste as a resource” OR "recycled material*" OR “secondary raw material*” OR “reusable material*”) AND TITLE-ABS-KEY (bio* OR organic)	34

Appendix 2: Table of the articles that were excluded, with the exclusion reason.

Nr.	Title	Author	Year	Country	Input material	Reason for exclusion
1	Recyclability, durability and water vapour adsorption of unstabilised and stabilised compressed earth bricks	Bruno, A.W., et al.	2020	UK	Compressed earth bricks	No LCA is conducted on the compressed earth bricks. the focus is on the quality of the material and not on the reuse or recyclability.
3	Environmental footprint of cultivating strawberry in Spain	Romero-Gámez, et al.	2020	Spain	Strawberry production system	The paper does not focus on the use of biowaste as an input.
4	Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres	Faraca, G., et al.	2019	Denmark	Hard plastic waste	The paper does not focus on the use of biowaste as an input.
6	Analysis of energy use and emissions of greenhouse gases, metals and organic substances from construction materials used for artificial turf	Magnusson, S., et al.	2017	Sweden	Recycled tires (RT), virgin thermoplastic elastomers (TPE), virgin ethylene propylenediene monomer (EPDM) and recycled EPDM (R-EPDM) from cables and automotive mats.	After a full text analysis, it was found that the paper does not conduct an LCA.
9	Comparison of end-of-life tire treatment technologies	Li, X., et al.	2010	China	Tires	No LCA is conducted in this paper. The paper focusses on end-of-life treatment technologies.
10	Life-cycle-based solid waste management.	Solano, E., et al.	2002	US	Municipal solid waste	Paper presents a comprehensive mathematical model for ISWM and does not actually conduct an LCA.