Use phase and end-of-life modeling of biobased biodegradable plastics in life cycle assessment: a review

Katrin Molina-Besch

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Abstract

Due to the negative environmental impacts along the life cycle of fossil-based plastics, there is an increased interest in the development of biobased and biodegradable plastics. Especially, biodegradable bioplastics possess different material characteristics than fossil-based plastics and can therefore be expected to perform differently during the product use and in end-of-life (EOL) phases. Thus, it is important to consider the material performance and behavior of biobased plastics in life cycle assessment studies. In practice, this is often a difficult task due to lack of data. The purpose of this review study is to analyze how contemporary LCA method models the use and EOL phases of biobased biodegradable plastics, with a specific focus on how the properties of these chemical novel materials are considered in LCA modeling. The first part of the review summarizes recommendations for the use phase and EOL modeling of biobased plastics. The second part analyzes 42 bioplastic LCAs in relation to these recommendations. The results of the review reveal that the use phase is commonly neglected in LCAs of bioplastics. Moreover, it is shown that EOL modeling in LCAs of biobased biodegradable plastics is often based on data that is non-specific for the analyzed material(s). The results of the review call for more research on the specific material properties of newly developed biobased biodegradable plastics, as these data are needed to decrease uncertainties in bioplastic LCAs.

Graphical abstract
Introduction

The environmental concerns connected to the extensive use of petroleum-based plastic products in modern society have led to intensive research activities to find alternative materials. Biobased and biodegradable plastics are seen as promising pathways by many authors, for example (Hattikaul et al. 2020), although their current use in society is still small. According to the general use of the term bioplastics in literature and industry, bioplastics can be (a) fossil-based and biodegradable, (b) biobased and nonbiodegradable as well as (c) both biobased and biodegradable (Dilkes-Hoffman et al. 2019). Today, most of the bioplastics used are so-called drop-in bioplastics (such as green polyethylene). These bioplastics are made of renewable resources, but they are chemically equal to their fossil-based counterparts and therefore nonbiodegradable. As a result, drop-in bioplastics perform basically in the same way as fossil-based plastics during industrial processing, product use and at the end of life (in, e.g., recycling processes). This review focuses on LCAs of biodegradable biobased plastics (BBPs) such as polylactic acid (PLA). BBPs are chemical novel materials with different material properties compared to the fossil-based plastics (and drop-in bioplastics) mostly used in society today (Spierling et al. 2020). In this article, the term fossil-based plastics (FPs) is used to refer to fossil-based non-biodegradable plastics (FPs).

To compare the environmental impact of newly developed bioplastics with the impact of petroleum-based plastics, the method of life cycle assessment (LCA) is commonly used. The LCAs performed on biobased plastics during the last two decades have shown that in many cases, biobased plastics lead to lower greenhouse gas emissions and lower nonrenewable energy use compared to their petroleum-based counterparts, for example (Spierling et al. 2018a). At the same time, it has been highlighted that performing LCAs of bioplastics is a difficult task due to many uncertainties about the life cycle of these relatively new materials (Hermansson et al. 2019). Examples include uncertainties about production processes, material characteristics in different applications, consumer acceptance and behavior, and material behavior in different waste management processes. In most cases, technical parameters of production processes and material characteristics can only be assessed based on laboratory experiments or pilot plants and the effects of upscaling remain unconsidered. LCAs that assess bioplastics over the complete life cycle are scare, most probably due to the difficulties of obtaining meaningful data for all life cycle (LC) phases. Previous reviews of bioplastic LCAs have concluded that many studies focus on the production phase in so-called cradle-to-gate LCAs, for example (Hottle et al. 2013). While data availability might be best for the production phase, it has also been shown that downstream processes and especially the use and end-of-life (EOL) phases can contribute significantly to the overall environmental impact of the bioplastic LC (Spierling et al. 2018a).

While bioplastics are commonly developed to replace FPs with the intention to reduce negative environmental impacts, it is important to recognize that a transition to BBPs can involve so-called burden-shifting (Bjørn et al. 2018). Burden-shifting can involve (1) the reduction of one type of environmental impact (e.g., fossil resource depletion) at the expense of increasing another type of environmental impact (e.g., eutrophication) and/or (2) the reduction of environmental impact in one life cycle phase (e.g., material production) at the expense of increasing the impact in another life cycle phase (e.g., product use) (Bjørn et al. 2018). Due to the risks of burden-shifting, it is important that bioplastic LCAs consider the full life cycle of the materials and that a comprehensive set of environmental impact categories is analyzed.

There are important differences between the life cycles of bioplastics and FPs. FPs are characterized by the use of fossil resources as feedstock and energy input to material production that commonly dominate the negative environmental impact along their life cycle, for example (Razza et al. 2015). Other important hot spots in the FPs life cycle include the end-of-life emissions, especially in the form of CO₂ emissions from waste incineration and microplastics in nature from littered plastics and mismanaged plastics waste disposal (Geyer et al. 2017). The impact of nonbiodegradable plastics leaking into nature, are, however not included in standard LCA impact assessment methods as these methods are still under development, for example (MarILCA, n.d.).

Biobased plastics on the other hand are characterized by the use of renewable resources as feedstocks, currently mainly in the form of crops such as corn, sugarcane, and potato. The agricultural processes for growing these crops constitute important hot spots in the life cycle of bioplastics (Weiss et al. 2012) due to especially the use of fertilizers, pesticides, irrigation water, and potential land use changes, for example (Escobar et al. 2018). Since production processes of bioplastics are immature in comparison with the processes in the petrochemical industry, energy use in the production phase can be another important hot spot (Changwichan et al. 2018). The environmental impact of BBPs at the EOL depends a lot on the available waste management infrastructure, since the potential benefits of biodegradability are lost if composting or anaerobic digestion facilities for
these relatively new materials are lacking (Zhu and Wang 2020).

Previous LCA reviews have focused on important methodological choices in LCAs of biobased materials in general (Pawelzik et al. 2013) and on methodological choices in LCAs that compare petrochemical and bioplastics (Bishop et al. 2021). Other reviews have analyzed bioplastic LCA results by looking at comparisons of bioplastics and petrochemical plastics, for example (Hottle et al. 2013; Yates and Barlow 2013), and by studying the environmental impact of different end-of-life routes for bioplastics (Spierling et al. 2018b, 2020). To complement previous studies, the purpose of this literature review is to analyze how contemporary LCA method models the use and EOL phases of biobased biodegradable bioplastics (BBPs). The focus of the review is on developing an increased understanding about how the fact that BBPs are chemical novel materials with different material properties (compared to FPs) is considered in LCA modeling of the use and EOL phases. Despite the fact that material properties of BBPs have a clear impact on the environmental impact of these materials along their LCs, previous LCA reviews have paid little attention to this aspect. Important material properties of BBPs that affect their environmental impact during the use and EOL phases include (but are not limited to) gas barrier and water vapor barrier properties (for packaging applications), material density, mechanical properties (e.g., for car parts or building material), and thermal properties.

**Methods**

The literature review encompassed the following steps: narrow literature search to identify search terms, literature search, selection and sorting of relevant literature, and analysis of selected literature. The literature review started with a narrow search in LUB search (an electronic literature search engine of Lund University) based on an initial list of search terms (see Table 1) that resulted in the identification of 14 relevant articles. The abstracts of the 14 articles were analyzed to identify a broader set of search terms (see Table 1) that were used for the subsequent broad search in the electronic databases Scopus and Web of Science that resulted in a total of 1170 hits. The following criteria were used to select the articles for the review.

1. The review is limited to peer-reviewed journal articles in English. Book chapters and reports published by industry, governmental, and nongovernmental organizations are excluded due to the potential lack of a peer-review process and a perceived higher risk of non-declared conflicts of interest. In addition, only LCAs that are published for the scientific community can be expected to take part in the scientific discourse about methodological developments of LCA.

2. The review is limited to articles that present method(s) and/or results of a LCA (or similar) to assess potential environmental impacts of BBPs. Review studies on BBPs that include results from environmental assessments are also included. Studies that are limited to analyzing the environmental impact of drop-in bioplastics (such as green PE and green PET) are excluded, because they do not differ in material properties (e.g., barrier properties) from their petroleum-based equivalents, and thus, they perform in the same way during the use phase and at EOL as FPs.

3. The scope of the selected LCAs must include either the use phase or the EOL phase of the analyzed bioplastic(s) since the review focuses on modeling of these life cycle phases.

4. The review considers publications from 2000 until 2021 because both technologies and LCA methodology older than 20 years are less relevant for ongoing research and development in this field.

Based on the selection criteria, 61 articles were identified as relevant. The reference lists of the selected 61 articles were reviewed which resulted in the identification of an additional 20 relevant articles. All selected 81 articles were sorted into two categories before the analysis: review studies (39 articles) and LCA studies (42 articles).

The analysis was performed in two steps. In the first step, the 39 review studies were analyzed to identify

| Table 1 | List of search terms used for the literature search |
|------------------------------------------|---------------------------------------------------|
| **Narrow search in database LUB search** | **Broad search in Scopus and Web of Science** |
| Prospective OR predictive OR future OR projecting AND (environmental AND (assessment or evaluation OR screening) OR LCA OR life cycle analysis OR life cycle assessment)) AND (materials OR packag* OR polymer OR plastic) | (Environmental assessment OR environmental screening OR environmental evaluation OR LCA OR life cycle analysis OR life cycle assessment OR sustainability assessment OR sustainability evaluation) AND (food packaging OR packaging material OR packag* OR film OR container OR biopolymer OR biocomposite OR bioplastic OR plastic) AND (ex-ante OR prospective OR predictive OR projecting OR future OR emerging) |

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recommendations for bioplastic LCAs regarding the use and end-of-life phase assessment. In the second step, the 42 LCA studies were analyzed in relation to the recommendations identified in step 1.

**Results**

The results presentation is structured in the following way. Firstly, the recommendations given for LCA of bioplastics (in relation to the use phase and end-of-life assessment) provided in the review articles are presented. The second part of the results section shows how the reviewed LCA studies of bioplastics for packaging applications (32 studies) and for non-packaging applications (10 studies) have modeled the use and end-of-life phases with particular focus on the recommendations provided earlier.

**Recommendations for bioplastics LCAs given in the review studies**

Of the 39 identified review studies, 18 studies provided recommendations for the use phase and/or end-of-life phase modeling in LCAs of bioplastics (see Table 2). For a complete list of all 39 review studies, please see the Supplementary information. Slightly more of the studies provided recommendations for both the use and EOL phase (8 studies) than commenting only on the use phase (6 studies) or only on the EOL phase (4 studies). It is important to consider that many of the review studies had a broad purpose which might explain why they do not provide any recommendations for use phase or EOL modeling.

Tables 3 and 4 list the recommendations provided in the review studies. Approximately one third (12) of the review studies provided recommendations for the use phase assessment. The most common recommendation was simply to include the use phase in the scope of bioplastic LCAs. Besides scope, another aspect highlighted in several reviews is the importance of considering the material properties of a particular bioplastic for a specific application which in most cases affects the impact during the use phase. Three reviews suggest that material properties are best considered in the functional unit definition of LCA. One study proposes scenario analysis as a way forward to address uncertainties about the material properties of newly developed bioplastics. Two of the reviews provide specific recommendations for the assessment of bioplastic packaging, one regarding scope and one regarding the influence of the bioplastic on food waste.

Table 4 lists the recommendations for the assessment of the EOL phase. The most common advice is to consider all parts of the plastics life cycle, which includes the advice to include the EOL phase. The recommendations for how to model the EOL impact of bioplastics are all addressing the fact that this impact is highly variable since there are many potential waste management processes and because there are many affecting factors. In addition, several reviews stress that there is great uncertainty about the end-of-life environmental impact of biodegradable plastics (Filiciotto and Rothenberg 2021; Yates and Barlow 2013) without formulating any related recommendation. The recommendations for the scenario and sensitivity analysis pinpoint the same aspect by proposing that the variability of EOL impacts of bioplastics should be assessed through scenarios. In addition to high variability due to the coexistence of different waste management processes in many contexts, it is also emphasized that LCAs of bioplastics should consider the impact of potential or future waste management pathways.

**Results of the reviewed LCAs**

Table 5 provides an overview of the 42 reviewed LCAs with regard to the type of BBP applications and the geographic context.

Figure 1 shows that the reviewed LCAs have been published relatively evenly spread over the last twenty years. However, most of the studies have been published from 2010 onwards. With regard to the geographical context of the LCAs (Fig. 2), the European context is clearly overrepresented, with 19 out of 32 packaging LCAs and 6 out of 11 non-packaging LCAs. The second most common context among the packaging LCAs is Asia (7 studies), followed by North America (3 studies), South America (2 studies) and Australia (1 study). PLA is the most assessed type of BBP for packaging applications in the reviewed LCAs, followed by films/multi-layer materials. In the LCAs of non-packaging applications, biocomposites, and thermoplastic starch (TPS)/starch-based plastics are most common (Fig. 3). Packaging is by far the most common application area for BBPs assessed in the reviewed LCAs (Fig. 4). Looking in more detail at the reviewed packaging LCAs, food packaging is the most common type of application area followed by unspecified packaging, food containers and non-food packaging. In this review, food containers are defined as packaging that does not prolong the shelf life of food, such take-away food or beverage containers.

Most (32 studies) of the reviewed LCAs include a comparison between the analyzed BBP(s) and FP(s). From an analysis of the studies’ conclusions, it can be seen that most studies (26 studies) present inconclusive result of the comparison (see Fig. 5) while only 6 studies state overall positive or negative results for BBPs (in comparison with FP). All those 6 studies are LCAs of packaging applications. Many studies motivate the overall inconclusive results with the fact that BBPs caused lower environmental impact in some impact categories but higher impact in others. A number of studies that analyze several BBPs in parallel to a number
Table 2 Overview of the review studies providing recommendations for use phase and EOL assessment of biobased plastics

| Authors, (year), journal | Purpose of the review (shortened)                                                                                                                                                                                                 | Recommendations for use-phase assessment provided | Recommendations for end-of-life assessment provided |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Bishop et al. (2021), Resources, Conservation and Recycling | “(This study) explores the growing collective of LCA studies that explicitly benchmark the environmental impacts of specific bioplastics against petrochemical plastics. […] The aim of this study was to review a large segment of the literature to clarify the state of knowledge, identifying key gaps in studies and therefore potential weaknesses in LCA results hitherto” | No                                                | Yes                                               |
| Brodin et al. (2017), Journal of Cleaner Production | “To focus on advances in the development of bioplastics from forestry resources.”                                                                                                                                                      | Yes                                                | Yes                                               |
| Chen and Patel (2012) Chemical Reviews | “To discuss the production processes of biobased monomers and polymers, to compare the thermal and mechanical properties of them, and to assess their environmental performance”                                                                 | Yes                                                | No                                                |
| Civancik-Uslu et al. (2018), Science of the Total Environment | “To identify what has been published so far about the environmental impacts of plastic composites and compounds with functional fillers and to understand if the use of fillers tends to decrease the environmental impacts” | Yes                                                | Yes                                               |
| de la Caba et al. (2019), Journal of Cleaner Production | “This review considers the potential of developing food packaging from food processing waste in order to create business for food industries, being aware of the food quality demanded by consumers and the environmental care demanded by institutions and society” | Yes                                                | No                                                |
| Dietrich et al. (2017), Sustainable Production and Consumption | “To discuss PHAs as promising biomaterials for current bioeconomy strategies and the process and product design criteria required to maximize the benefits of their implementation” | Yes                                                | No                                                |
| Fagnani et al. (2021), ACS Macro Letters | “To capture a snapshot of what recent synthetic polymer chemists consider as sustainable polymers”                                                                                                                                 | Yes                                                | Yes                                               |
| Heimersson et al. (2014), New Biotechnology | “To identify LCA methodological pitfalls as well as opportunities in the challenge to gain a meaningful perspective of environmental impact for open, mixed-culture PHA production that utilizes waste as feedstock” | Yes                                                | Yes                                               |
| Hermansson et al. (2019), Journal of Cleaner Production | “To illustrate the type of information that can be obtained from mining and refining information from earlier life cycle assessment studies and to provide guidance on environmental opportunities and challenges specific for carbon fiber reinforced polymers with a focus on the shift to lignin as a feedstock for carbon fibers and on recycled carbon fibers in composites” | Yes                                                | No                                                |
| Hottle et al. (2013), Polymer Degradation and Stability | “To present a broad summary of the current status of environmental impact assessments for biopolymers”                                                                                                                                 | No                                                | Yes                                               |
of fossil-based benchmarks conclude that specific (but not all) BBPs showed lower environmental impact compared to specific FPs. A third reason for inconclusive results is the high variability of potential results due to uncertainties in the inventory data of BBPs.

**Use phase assessment in the reviewed LCAs**

According to the recommendations in the review studies (Table 3), the use phase should be included in the scope of BBPs’ LCAs and the influence of material properties on the functionality/performance of the plastic during the use phase should be considered. Figure 6 shows that more than half of the reviewed LCAs exclude the use phase without providing information about how the assessed BBP performs during product use in comparison with petroleum-based plastics. This result applies for the sum of all LCAs and holds also for the LCAs in each application area (food packaging, other packaging, and non-packaging). Looking at the complete sample, the second most common approach is to exclude the use phase and to perform parallel experiments/tests that provide proof that the analyzed BBP product performed in a similar manner as products made of FPs. Figure 6 shows also that in food packaging LCAs, it is more common to assume the same functionality during the use phase than to perform tests for validation. For all other types of packaging (food containers, non-food and unspecified), it is instead more common to perform parallel tests on important performance indicators. In most cases, these were experiments to measure mechanical properties of the materials. In the complete sample of the 43 reviewed LCAs, there is only one studies that calculates the specific use phase impact of the analyzed BBP product in comparison with the use phase impact of a comparable fossil-based plastic product. The

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**Table 2 (continued)**

| Authors, (year), journal | Purpose of the review (shortened)                                                                 | Recommendations for use-phase assessment provided | Recommendations for end-of-life assessment provided |
|--------------------------|------------------------------------------------------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Mendes and Pedersen (2021), Trends in Food Science & Technology | “To present in a holistic perspective the most relevant parameters that need to be considered for sustainability in food packaging and aims to increase the awareness of food and packaging producers to create effective sustainable packaging materials for foods” | Yes                                              | No                                               |
| Pawelzik et al. (2013), Resources, Conservation and Recycling  | “To provide an overview of key issues and methodologies explicitly pertinent to the LCA of bio-based materials” | No                                               | Yes                                              |
| Philip et al. (2013), New Biotechnology                       | “To look at trends and applications for biodegradable and bio-based plastics, to examine issues that inhibit their uptake, and to look at policy measures that can be implemented to improve their market penetration” | Yes                                              | Yes                                              |
| Spierling et al. (2018b), Procedia CIRP                       | “To give an insight into the opportunities and challenges of biobased plastics as a building block of a circular economy” | No                                               | Yes                                              |
| Spierling et al. (2018a), Journal of Cleaner Production        | “To provide an overview on the sustainability assessment of bio-based plastics, presenting the currently common assessment practice and related issues, highlighting methodology gaps” | Yes                                              | Yes                                              |
| Venkatachalam et al. (2018), Procedia CIRP                    | “To provide a short overview on the different LCA studies conducted on the biopolymers and different studies that integrate LCA and ecodesign to improve the product characteristics on a long term” | Yes                                              | Yes                                              |
| Vilaplana et al. (2010), Polymer Degradation and Stability     | “To cover the environmental implications of the design and use of bio-composites from a sustainable perspective” | Yes                                              | Yes                                              |
| Weiss et al. (2012) Journal of Industrial Ecology              | “To present a meta-analysis that summarizes the results of the existing LCA literature on biobased materials” | No                                               | Yes                                              |
### Table 3  Recommendations for bioplastic LCAs in relation to product use phase (from review studies)

| Topic area                          | Recommendation                                                                                                                               | References                                                                                     |
|-------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| **LCA scope**                       | Environmental assessments of bioplastics should have a cradle-to-grave scope/should include all parts of the product life cycle.            | Brodin et al. (2017), Civancik-Uslu et al. (2018), Fagnani et al. (2021), Heimersson et al. (2014) and Vilaplana et al. (2010) |
|                                     | The environmental impact of bioplastic packaging should be assessed together with the impact of the packed food.                           | Mendes and Pedersen (2021)                                                                      |
| Material properties and functional unit | Comparing bioplastics with other materials on a kg basis is problematic because material properties differ. Evaluating the use phase of bioplastics in comparative LCA studies should consider the relevant material properties of the bioplastic for the context of a specific application. | Chen and Patel (2012), Civancik-Uslu et al. (2018) and Dietrich et al. (2017)                    |
|                                     | For comparative LCAs of bioplastics, it is very important to define a proper functional unit serving the same function to be able to consider differences in material properties. | Civancik-Uslu et al. (2018), Hermansson et al. (2019) and Philp et al. (2013)                     |
|                                     | Environmental assessment of bioplastics for food packaging applications should consider how food waste is affected, both due to the effect on the shelf life of the packed food but also due to a potential effect on consumer behavior. | de la Caba et al. (2019)                                                                      |
| **Scenario and sensitivity analysis** | Scenario analysis can be applied for the use phase if there is uncertainty about the properties of a new bioplastic.                     | Heimersson et al. (2014)                                                                       |

### Table 4  Recommendations for bioplastic LCAs in relation to end-of-life phase (from review studies)

| Topic area                          | Recommendation                                                                                                                               | References                                                                                     |
|-------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| **LCA scope**                       | Environmental assessments of bioplastics should have a cradle-to-grave scope/should include all parts of the product life cycle.            | Brodin et al. (2017), Civancik-Uslu et al. (2018), Fagnani et al. (2021), Heimersson et al. (2014) and Vilaplana et al. (2010) |
|                                     | Biobased plastics might involve sequestration of biogenic carbon in landfills and therefore an inclusion of the EOL phase is important for comparisons between biobased plastics and inorganic materials. | Pawelzik et al. (2013) and Philp et al. (2013)                                                   |
| **Modeling of waste management processes** | The assessment of the end-of-life environmental impacts of bioplastics must consider that recyclability and biodegradability is affected by the specific context (e.g., consumer behavior, waste collection and sorting system, climatic conditions, etc.). | Heimersson et al. (2014)                                                                       |
|                                     | EOL assessment of bioplastics should cover all major waste management options (landfilling, composting, incineration, digestion, and recycling). | Weiss et al. (2012)                                                                            |
|                                     | An understanding of consumer behavior with regard to waste sorting is important for a proper assessment of the EOL impact of bioplastics.   | Heimersson et al. 2014; Hottle et al. (2013)                                                    |
| **Scenario and sensitivity analysis** | Scenario analysis and sensitivity analysis of all viable alternatives for bioplastic end-of-life is important, because environmental impact of bioplastic end-of-life varies a lot between different waste management processes and depending on the assumptions taken. | Hottle et al. (2013) and Bishop et al. (2021)                                                   |
|                                     | The assessment of the end-of-life environmental impact of bioplastics should not focus on currently existing waste management processes for plastics but also explore the potential of new waste management pathways for the future. | Hottle et al. (2013) and Philp et al. (2013)                                                    |
|                                     | EOL assessment of bioplastics should include recycling as a scenario even though this is currently commonly not a factual waste management route for bioplastics. | Spierling et al. (2018a, b)                                                                    |
Table 5 Overview of the reviewed LCAs

| Author (year), journal | Type of product/application | Geographic context |
|------------------------|-----------------------------|--------------------|
| Amasawa et al. (2021), Environmental Science & Technology | Material: poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBHHX); Two specific single-use plastic products for assessment: a produce bag and a spoon | Asia |
| Beigbeder et al. (2019), Waste Management | PP with wood flour (PP/WF) and PLA with flax fibers (PLA/Fl). P/WF composite is mainly used for decking application, while PLA/Fl can be found in the automotive sector | Europe (France) |
| Benetto et al. (2015), Journal of Cleaner Production | Multilayer film made of thermoplastic starch and PLA | Europe |
| Bohlmann (2015), Environmental progress | Product: yoghurt packaging; bioplastic: PLA (in comparison with PP) | North America |
| Changwichan et al. (2018), Sustainability | Disposable takeaway food boxes produced from different bioplastics (PLA, PHAs, and PBS from sugarcane and cassava) | Asia |
| Choi et al. (2018), Sustainability | Packaging films made of PLA and PLA/PPB compared to LDPE film | Asia |
| Cosate de Andrade et al. (2016), Journal of Polymers and the Environment | PLA | South America |
| Deng et al. (2013), Biofuels, Bioproducts and Biorefining | Wheat gluten powder derived packaging film | Europe |
| Dilkes-Hoffman et al. (2018), Journal of Cleaner Production | Biodegradable PHA-TPS layered material (used as packaging for beef and cheese) | Australia |
| Eerhart et al. (2012), Energy and Environmental Science | Comparison of PEF and PET on a per kg basis—not for a specific application | Europe |
| Gironi and Piemonte (2011), Energy Sources Part A: Recovery, Utilization & Environmental Effects | Shoppers made from Mater-Bi and polyethylene (PE) | Europe |
| Guo and Murphy (2012), Journal of Polymers and the Environment | Products: a coolbox, a display board, a refractory lining former for concrete formwork and two trough molds (void-formers for constructing flooring); Bioplastics: three starch–PVOH based biopolymers, a wheat-based foam (WBF), a potato starch-based foam (PSBF) and a maize starch-based foam (MSBF) | Europe |
| Guo et al. (2011), Bioresource Technology | Starch–polylactic acid biopolymer packaging | Europe |
| Haylock and Rosentrater (2018), Journal of Polymers and the Environment | PLA composites (with different organic and inorganic fillers) | North America (USA) |
| Hermann et al. (2011), Polymer Degradation and Stability | Starch, polylactic acid (PLA), starch/polyacrolactone (starch/PCL), polybutyrate-adipateterephthalate (PBAT) and polyhydroxyalkanoates (PHA) | Europe |
| Hermann et al. (2010), International Journal of Life Cycle Assessment | PLA-laminates with different coatings that are used in direct food contact | Europe |
| Hottle et al. (2017), Resources, Conservation and Recycling | PLA and TPS compared to PET, Bio-PET, HDPE, Bio-HDPE, LDPE, and Bio-LDPE | North America (USA) |
| Ingrao et al. (2015), Science of The Total Environment & Ingrao et al. (2015), Journal of Cleaner Production | Expanded PLA food containers | Europe |
| Khoo and Tan (2010), International Journal of Life Cycle Assessment | Biobased bag (made from polyhydroxyalkanoate, PHA) | Asia |
| Lecceta et al. (2013), Journal of Cleaner Production | A new biodegradable chitosan–based film (in comparison with a commercial PP film) | Europe |
| Lejarkpai et al. (2016), Journal of Cleaner Production | Biodegradable packaging films made from soy protein (by-product of soy oil industry), chitosan from the skeleton of crustaceans, and agar from marine seaweeds. | Europe |
| Lorite et al. (2017), LWT—Food Science and Technology | PLA containers (compared to PET & PS containers) | Asia |
| Madival et al. (2009), Journal of Cleaner Production | PLA clamshell (in comparison with PET and PS clamshell) | North America |
| Maga et al. (2019), Resources, Conservation and Recycling | PLA packaging | Europe |
| Papong et al. (2014), Journal of Cleaner Production | PLA (in comparison with PET) for bottles | Asia |
| Author (year), journal | Type of product/application | Geographic context |
|------------------------|----------------------------|-------------------|
| Piemonte (2011), Journal of Polymers and the Environment | Shells of PLA and of Mater-Bi for food packaging | Europe |
| Piemonte and Gironi (2011), Environmental Progress & Sustainable Energy | PLA bottles (in comparison with PET bottles) | Europe |
| Pietrini et al. (2007), Biomacromolecules | Different poly(3-hydroxybutyrate) (PHB)-based composites used for cathode ray tube (CRT) monitor housing, and the internal panels of an average car. PHB fillers are sugar cane bagasse (SCB) and organophilic montmorillonite (OMMT) | Europe |
| Razza et al. (2015), Journal of Cleaner Production | Starch-based cushioning packaging (in comparison with EPS) | Europe |
| Ribeiro et al. (2013), Materials & Design | Biodegradable composites made of TPS and PLA (compared to PP) | Europe (Portugal) |
| Rodriguez et al. (2020), Data in Brief | Composite material made of banana fibers, HDPE and PLA | South America |
| Rossa et al. (2015), Journal of Cleaner Production | Polylactic acid (PLA) and thermoplastic starch (TPS), used for dry packaging | Europe |
| Schmehl et al. (2008), Journal of Polymers and the Environment | Product: a car-part (a body component of a MAN-passenger-bus), bioplastic: a composite material (material system based on natural fibers and PTP, a vegetable based thermoset resin) | Europe (Germany) |
| Schmehl et al. (2008), Journal of Cleaner Production | PLA for drinking cups (to compare with PS cups) | Europe (Germany) |
| van der Harst et al. (2014), Science of the Total Environment | Beverage cups made from polystyrene (PS), polylactic acid (PLA) and paper lined with bioplastic | Europe (Netherlands) |
| Vercalsteren et al. (2010), International Journal of Life Cycle Assessment | PLA cups | Europe (Belgium) |
| Vidal et al. (2007), Journal of Polymers and the Environment | Biodegradable multilayer film—based on modified starch and polylactic acid (PLA) | Europe |
| Vidal et al. (2007), Journal of Polymers and the Environment | Biodegradable multilayer film—based on modified starch and polylactic acid (PLA) | Europe |
| Vidal et al. (2007), Journal of Polymers and the Environment | Biodegradable multilayer film—based on modified starch and polylactic acid (PLA) | Europe |
| Yano et al. (2014), Waste management & research; the Journal of the International Solid Wastes and Public Cleansing Association, ISWA | PLA and PLA mixed with polybutylene succinate adipate (PBSA) in bags | Asia (Japan) |
| Ögmundarson et al. (2020), GCB Bioenergy | PLA for food packaging | North America (USA) |
LCA by Schmehl et al. (2008) calculates the difference in fuel consumption during the use phase of a bus component based on the differences in the weights of the components. It must, however, be mentioned that several other biocomposite LCAs follow the same approach, for example (Tadele et al. 2020), but these studies were excluded from the review because the polymer matrix in the analyzed biocomposites is fossil based (only the filler is biobased).

Figure 7 shows the distribution of different approaches taken regarding the use phase based on the types of BBPs that are analyzed in the reviewed LCAs. It is visible that none of the PLA LCAs considers the materials’ performance during the use phase. It can moreover be seen that studies that consider material functionality during the use phase are most commonly assessing multilayer films and blends. Table 2 in the supplementary information combines the information about the type of biobased plastics, plastics application type, and approach taken in the use phase assessment in the reviewed LCAs. It shows that multilayer food packaging is overrepresented among the studies that demonstrate or assume similar functionality during the use phase. Besides that, it can be concluded that exclusion of the use phase without any reference to the functionality of BBP(s) during the use phase is a common approach in LCAs of all kinds of biopolymers (and independent from application area).

Another analyzed aspect is whether there are any differences in the comparative LCA results (comparison between BBPs and FPs) depending on the taken use phase approach. The approach taken regarding the use phase does not appear to have any effect on the comparative results (see Fig. 8). However, it is interesting to see that all LCAs that assume or demonstrate the same functionality during the use phase include a comparison with FPs which is not the case among studies that do not refer to the materials’ functionality. When comparing studies that assume the same functionality of the assessed bioplastics (8 studies) and studies that demonstrate
similar functionality (7 studies), a slight difference in results is visible: 4 (out of 8) studies that assume same functionality and 6 (out of 7) studies that demonstrate similar functionality present unconclusive results regarding the environmental impact of the assessed bioplastics against a fossil-based benchmark. Among the studies that assume the same functionality, 2 studies conclude that there was a clear environmental gain from switching to BBPs (in the assessed case) while two studies conclude the opposite (clear environmental loss through replacing FP with BBP). Among the studies that demonstrate similar functionality, only one (out of 7) concludes that overall, the bioplastic reduced environmental impacts compared to fossil based.

The analysis showed moreover that approximately half of the studies that assume or that demonstrate similar material functionality discuss in their conclusions the importance of considering the performance of the assessed bioplastics during the use phase. In contrast, none of the studies that exclude the use phase without any reference to the use performance of the BBP(s) mention this aspect in their conclusions.

**End-of-life phase assessment in the reviewed LCAs**

Based on the recommendations of the review studies, the EOL of bioplastics should be included in LCAs. All of the
analyzed LCAs include the EOL phase, but this result is influenced by the selection criteria of the review. Since the purpose of the review is to understand how the use and EOL phase of BBPs are modeled in LCAs, studies with a cradle-to-gate scope were excluded. During the literature search and selection, it became clear that there are many LCAs of bioplastics with a cradle-to-gate scope, which has also been described in other LCA reviews, for example (Hottle et al. 2013). Figure 9 lists the waste treatment processes assessed in the reviewed LCAs. It shows that across all applications, composting, incineration, and landfill are the most commonly assessed treatment processes.

Several review studies highlight that scenario and sensitivity analyzes are an important approach to consider variability and uncertainties about the EOL impact of bioplastics in LCAs (see Table 4). Approximately one fourth of the reviewed LCAs focus on only one waste management (WM) scenario without considering that the EOL impact of bioplastics commonly varies between different potential WM scenarios (Fig. 10). Approximately half of the LCAs assess 2, 3, or 4 WM scenarios while only about 15% of the LCAs assess 5 or more WM scenarios. A waste management scenario is for the purpose of this literature review defined as the specific waste treatment process or combination of waste treatment processes assessed in an LCA, such as a scenario with 100% landfill or a scenario with 50% incineration and 50% composting. In contrast, a sensitivity analysis of the EOL data is concerned with assessing the influence of variations in specific datasets of EOL processes, such as the rate of biodegradation of bioplastics in landfills or composting facilities.

A broad range of different waste management scenarios is considered in the reviewed LCAs. Figure 10 lists waste management scenarios assessed in the reviewed LCAs.

Fig. 8 Relation between the use phase approach and the comparative LCA results (number of studies)

Fig. 9 Types of waste treatment processes assessed in the reviewed LCAs (number of studies sorted into different types of processes)
Approximately one third of the LCAs focus on one scenario while two thirds assess between 2 and 5 different scenarios in parallel. Among studies that focus on one process, composting is most commonly assessed, followed by incineration. The most common combinations of WM processes assessed in parallel are (1) landfill, incineration, composting, recycling, and (2) landfill, incineration, composting (Fig. 10).

Figures 11 and 12 show which share of the LCAs include different types of WMPs, divided into packaging (Fig. 11) and non-packaging applications (Fig. 12). Independent from the type of application, incineration, industrial composting, and landfill are the most commonly assessed processes. Since packaging applications of bioplastics usually are disposable/short-lived while non-packaging applications are commonly products with a longer lifetime, it is relevant to look at the differences in the considered waste management processes between the packaging and non-packaging LCAs. Home composting and littering are only considered in the non-packaging LCAs while chemical recycling is only considered in packaging LCAs. It is also visible that packaging LCAs assess recycling and incineration more frequently than non-packaging LCAs. In contrast, the non-packaging LCAs assess landfill and anaerobic digestion slightly more frequently than the packaging LCAs.

Since many of the analyzed LCAs compare several EOL processes for BBPs, the conclusions of the studies were analyzed with regard to the identified most preferable EOL process (see Fig. 13). It was found that across
all applications and for packaging, recycling is the most commonly identified preferable EOL process for BBPs. On the other hand, for non-packaging applications, composting is slightly more preferable (identified by 3 compared to 2 studies that identified recycling as most preferable EOL route).

Since bioplastics are currently only used to a minor extend in society, there is a lack of material-specific data about inputs (material and energy) and outputs (emissions and waste) from treating BBPs in common waste management processes. Life cycle inventory (LCI) data for waste treatment of BBPs are therefore (in most cases) unavailable in LCA databases and must be collected from other data sources. In the reviewed LCAs, it was found that most authors (approx. 60%) use a combination of secondary data and assumptions to model the LCI of BBPs’ waste treatment (see Fig. 14). Approximately 30% of the studies combine primary data from different sources with secondary data and assumptions. The reliance on secondary data is more common in the reviewed packaging LCAs than in the non-packaging studies. Sources of primary data in the reviewed LCAs are experiments (5 studies), industrial waste management plants (5 studies), pilot plants (2 studies), simulation (1 study), and expert judgment (1 study).

The most difficult part of modeling the EOL of BBPs is future waste management processes that currently do not exist or that currently do not treat BBPs. In the reviewed LCAs, recycling, composting, and anaerobic digestion (AD) are modeled as future or potential waste management processes. The figures below show the distribution among different data sources for modeling recycling (Fig. 15), composting (Fig. 16), and AD (Fig. 17). It is interesting that while literature is the most common data source for composting and AD, for recycling life cycle inventory (LCI) databases are most common. Moreover, it can be seen that primary data from pilot plants, experiments, or industry are...
used in 38% of the recycling models, in 43% of the AD models but only in 21% of the composting models.

Since many BBPs are chemical novel materials (in comparison with conventional FPs), it is relevant to analyze to what extend the reviewed LCAs used material-specific data when modeling future EOL processes (see Fig. 18). While for composting and AD, the use of partly material-specific data is most common, for recycling mainly data for recycling of FPs is used. Especially among the packaging LCAs, also for composting the use of nonmaterial specific data is common practice (in this case data for generic biowaste is used). Among the studies that combine material-unspecific with material specific data (shown as “partly” in Fig. 18), it is common to consider the specific material composition (stochiometric or based on lab analysis), the specific biodegradation rate (from literature or based on performed
biodegradation tests), and material-specific results from sorting tests (for recycling).

Figure 19 combines the results about the identified most preferable EOL process for BBP(s) with the results about the types of input data for EOL modeling. For this part of the analysis, literature and LCI database data were grouped as secondary data while pilot plant, experimental, and industry data were grouped as primary data. In addition, it was considered whether or not material-specific data were included in the EOL model. It is visible that there is an even distribution of the different types of data used for modeling of recycling and composting by studies that identify recycling and composting as preferable EOL processes. Based on that result, it appears that the type of input data used has no direct influence on the EOL results. When it comes to the other three processes, it is visible that only studies using secondary data identify them also as most preferable. In the case of landfill, this refers to only one study that uses secondary, non-material-specific data.

While the assessment of several WM scenarios is common in the reviewed LCAs (Fig. 20), performing sensitivity analyses on EOL data is far more uncommon (Fig. 21) despite the fact that uncertainties in EOL data have been highlighted as an issue in LCAs of bioplastics (Table 4). More than half of the reviewed LCAs do not perform any sensitivity analyses on EOL data. Among the studies that perform sensitivity analyses on EOL data, the rates of material degradation (in landfill, composting, AD) and methane emissions from biodegradation of bioplastics (in landfills or AD facilities) are the most commonly assessed parameters (see Table 6). Other EOL parameters assessed include the sorting efficiency and the substitution rates for recycled bioplastics.
### Discussion

In contrast to what several of the analyzed review studies recommend, the majority of the reviewed LCAs of BBPs exclude the use phase. In 26 of the 42 LCAs, the use phase was excluded without further reference to how the analyzed BBP(s) perform during product use. In these studies, the authors seem to assume that there is no major difference between the BBP(s) and its/their fossil-based counterparts with regard to the use phase. It might also imply that only those types of BBPs that perform similar to FPs in important applications are assessed in LCAs. On one hand, this approach appears comprehensible because it could be considered irrelevant to assess a material that performs worse than FPs. On the other hand, this approach conflicts with the very idea of life cycle thinking, i.e., an interest in the overall environmental impact of a product over its complete life cycle (in contrast to analyzing only selected life cycle phases). In addition, it also disregards the possibility that BBPs could perform better than FPs during product use. In approximately one third of the LCAs, the performance of the BBP(s) during product use was considered or discussed in some way. It is interesting that food packaging LCAs more commonly assumed similar functionality of BBPs while in studies of other applications, it was more common to perform experiments to validate material functions. This difference might be due to that packing and shelf life tests are more resource and time intensive in comparison with measurements of mechanical properties.

Zooming in on the use phase of food packaging, a practical problem of validating comparable barrier properties for newly developed BBPs is that material production and processing usually cannot be performed in a comparable way to fossil-based plastic packaging. Differences in production scale and in processing technologies for specific polymers inevitably lead to an unfair comparison. These problems have also been discussed by other authors but with a focus on the production phase of bioplastics (problem of incomparable production data). Tecchio et al. (2016) propose a method to estimate the environmental impact of polybutylene succinate (PBS) production through a scale-up protocol using data from pilot-plant production. To consider polymer-specific differences when increasing the production scale, they produce both PBS and a commercially available reference polymer (PET) in the same pilot plant. Following the same way of thinking, it would be interesting to produce fossil-based reference polymers under pilot- or laboratory-scale conditions and then measure their material properties to get a better idea about the effect of upscaled production and of optimized processing technology on the material properties of specific polymers.

The reviewed LCAs are more aligned to the recommendations for EOL modeling provided than to the ones for the use phase. Both the inclusion of the EOL phase and comparing several EOL scenarios containing potential future scenarios (composting and AD) is common practice in most of the reviewed LCAs. At the same time, it must be highlighted that the uncertainties in the underlying data for modeling the EOL are rarely analyzed in sensitivity analyses. Moreover, the review showed that less than half of the reviewed LCAs collected primary data to model future EOL processes of BBPs (namely recycling, composting, and AD). In addition, 70% of the reviewed packaging LCAs do not consider any material-specific data when modeling recycling, and 40% of them do not consider any material-specific data when modeling composting. There is a risk that the use of non-material specific data for modeling EOL of BBPs leads to a systematic under- or overestimation of their actual EOL impact.

Considering the results about EOL modeling, it appears surprising that few of the reviewed studies highlight the need for better EOL data. The negative environmental impact of FPs in the currently dominating waste management infrastructure (landfill and incineration) and the global problem of plastic waste leakage into nature are among the most important reasons for the development of biodegradable bioplastic alternatives. A more frequent use of sensitivity analyses on the EOL data in BBP LCAs is advisable and can contribute to more careful statements about the pros and cons of different EOL pathways for BBPs. At the same time, to increase the value of LCA results for the development of bioplastics, more and better EOL data is urgently needed. To make sure that new BBPs are developed and improved for minimized negative environmental impact at their EOL, it is
of high importance that (1) more material-specific LCI data for BBPs is generated and published, (2) that LCA methods are further developed to utilize results from EOL experiments and pilot-plants to model future waste treatment processes, and (3) that life cycle impact assessment methods are developed that consider the environmental impact of plastic waste leaking into nature.

Based on the analysis of the EOL results of the reviewed LCAs, at first, recycling appears as the most beneficial EOL route for BBPs. However, since only one third of the LCAs that identified recycling as best EOL route modeled based on primary and material-specific data, the benefit of recycling BBPs compared to composting and AD is not clearly supported based on the review results.

Concluding remarks

To minimize pollution and negative impact on ecosystems, research, design, and development of BBPs that can replace FPs in society rely on guidance from environmental assessments namely LCA. As highlighted by several authors (Hermansson et al. 2019), LCAs of newly developed materials or technologies are a difficult task due to unavailability of input data and uncertainties about the future. The purpose of this literature review is to analyze how contemporary LCA method models the use and EOL phases of biobased plastics with a focus on the consideration of material properties. BBPs are chemical novel materials that possess other material properties than FPs, and therefore, they behave differently during product use and in the EOL processes (such as recycling). Despite the importance of material properties for the environmental impact in the use and EOL phase of BBPs, these two life cycle phases have received considerably less attention in bioplastic LCAs than the production phase. The results of this review show that the use phase is a neglected phase in many LCAs of BBPs. While this practice is understandable due to uncertainties about material properties and performance of BBPs in the use phase, it is important that measurement methods for key material performance parameters and for a translation of the results of these measurements into LCI data in the early stages of material development are established. The review results demonstrate moreover that EOL modeling in LCAs of BBPs in many cases is based on uncertain and non-material-specific data. The effects of using this kind of data are seldom analyzed. These results highlight that more research is needed that can contribute with data for modeling the EOL impact of BBPs. It is hereby of outmost importance to combine development of BBPs with research into development and improvement of waste treatment and material recycling technologies, so that both uncertainties about the material performance in EOL processes and about the new waste treatment technologies can be reduced.

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Data availability The data from the literature review are available from the corresponding author on reasonable request.

Declarations

Competing interests The author has no relevant financial or non-financial interests to disclose.

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Authors and Affiliations

Katrin Molina-Besch

Katrin Molina-Besch katin.molina-besch@plog.lth.se

1 Division of Packaging Logistics, Department of Design Sciences, Lund University, Lund, Sweden

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