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Review article

Sustainability assessments of bio-based polymers

Troy A. Hottle [a,*], Melissa M. Bilec [b], Amy E. Landis [c]

[a] Arizona State University, School of Sustainable Engineering and the Built Environment, 370 Interdisciplinary Science and Technology Building 4 (ISTB4), 781 East Terrace Road, Tempe, AZ 85287-6004, USA
[b] University of Pittsburgh, Civil and Environmental Engineering, 153 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261-3949, USA
[c] Arizona State University, School of Sustainable Engineering and the Built Environment, 375 Interdisciplinary Science and Technology Building 4 (ISTB4), 781 East Terrace Road, Tempe, AZ 85287-6004, USA

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ABSTRACT

Bio-based polymers have become feasible alternatives to traditional petroleum-based plastics. However, the factors that influence the sustainability of bio-based polymers are often unclear. This paper reviews published life cycle assessments (LCAs) and commonly used LCA databases that quantify the environmental sustainability of bio-based polymers and summarizes the range of findings reported within the literature. LCA is discussed as a means for quantifying environmental impacts for a product from its cradle, or raw materials extraction, to the grave, or end of life. The results of LCAs from existing databases as well as peer-reviewed literature allow for the comparison of environmental impacts. This review compares standard database results for three bio-based polymers, polylactic acid (PLA), polyhydroxyalkanoate (PHA), and thermoplastic starch (TPS) with five common petroleum derived polymers. The literature showed that biopolymers, coming out of a relatively new industry, exhibit similar impacts compared to petroleum-based plastics. The studies reviewed herein focused mainly on global warming potential (GWP) and fossil resource depletion while largely ignoring other environmental impacts, some of which result in environmental tradeoffs. The studies reviewed also varied greatly in the scope of their assessment. Studies that included the end of life (EOL) reported much higher GWP results than those that limited the scope to resin or granule production. Including EOL in the LCA provides more comprehensive results for biopolymers, but simultaneously introduces greater amounts of uncertainty and variability. Little life-cycle data is available on the impacts of different manners of disposal, thus it will be critical for future sustainability assessments of biopolymers to include accurate end of life impacts.

1. Introduction

As biopolymers capture a larger market share, the measurement of their life cycle environmental impacts will be important to enable consumers and producers to identify more sustainable methods of use, production, and disposal for such products. This paper summarizes the range of reported findings from peer-reviewed life cycle assessments (LCAs) and commonly used LCA databases. LCA is a tool that quantifies the environmental sustainability of bio-based polymers from their 'cradle to grave'. A review of LCAs and LCA databases provides the research and polymer community with guidance toward the use of LCA in furthering the sustainability of the use, design, and disposal of bio-based polymers.

* Corresponding author. Tel.: +1 740 323 6627; fax: +1 480 965 0557.
E-mail addresses: troy.hottle@asu.edu (T.A. Hottle), mbilec@pitt.edu (M.M. Bilec), amy.landis@asu.edu (A.E. Landis).

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Plastics are used in all aspects of life including textiles, electronics, healthcare products, toys, packaging for foods, and many other goods. Approximately 31 million tons of plastic were used in the United States in 2010 with 14 million tons used in packaging, 11 million tons used in durable goods, and 6 million tons used in non-durable goods such as disposable diapers, cups, and plates [1]. Globally, plastic production exceeded 260 billion kilograms of plastic in 2009 [2]. According to the US Census Bureau the population of the US in 2010 was nearly 309 million people [3], which means an average of about 200 pounds of plastic per person was consumed that year.

Currently the dominant feedstocks for plastic production are derived from the fossil fuel industry. The chemistry of plastics lends itself to the readily accessible constituents of petroleum and natural gas. These sources have been able to provide reliable, consistent feedstocks for plastics development over the last 60 years. Over time, plastics have become more and more prevalent in daily life and new technologies are improving the performance of plastics, but just as gasoline and diesel will decrease in availability due to the increasing cost or scarcity of petroleum and other fossil-based fuels, so too will plastics made from fossil resources [4]. This increasing scarcity of resources emphasizes the need for alternative methods of creating plastics. Further, if resource availability were not a concern, it would be desirable to find methods of production that decrease the environmental impacts of ubiquitous materials because of the sheer scale of the industry. Petroleum-based plastics are crafted from carbon that has been locked up in the earth for millions of years. If this carbon were released through the incineration of the plastics, or some other form of degradation, it would result in a net increase of greenhouse gases in the atmosphere.

Plastics have different useful lifespans and are disposed of in a number of ways with varied recycling rates. According to the US Environmental Protection Agency (EPA), in 2009, plastics contributed to 12%, by weight, of the municipal solid waste (MSW) in the US, and 7% of plastics that were disposed of in MSW were recovered for recycling, though recovery rate is not necessarily indicative of a final recycling rate. Of total plastics, about 93% end up in a landfill or are incinerated. Generally, 12% of MSW that is not recovered is incinerated as a waste management strategy. When burned, 1 kg of plastic produces an average of 2.8 kg of carbon dioxide [5]. While overall recovery of plastics for recycling was only 7%, recovery of certain plastic containers is more significant. Polyethylene terephthalate (PET) soft drink bottles were recovered at a rate of 28% in 2009, while high-density polyethylene (HDPE) milk and water bottles were estimated at about 29%. Packaging and nondurable plastics in MSW totaled 19.2 million tons, of which 9% were recovered [6].

Biopolymers come in many different forms; they can be derived from renewable resources and may not be defined within the traditional plastics classification numbering system 1–6, like polylactic acid (PLA) [7] or they can be partially made from renewables and synthesized like traditional plastics as in the case of bio-based PET [8,9]. Biopolymers offer a renewable alternative to traditional petroleum-based plastics and can be derived from a wide variety of feedstocks including agricultural products such as corn or soybeans and from alternative sources like algae or food waste [10–12]. Biopolymers can replace petroleum-based polymers in nearly every function from packaging and single use to durable products.

Biopolymers are being designed with features such as biodegradability and compostability, which are standardized in the US according to ASTM D6400-04 Standard Specification for Compostable Plastics, ASTM D6868-03 Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates, and ASTM D5338-98(2003) Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions [13–15]. Biopolymers offer the opportunity to reduce fossil resources required to produce the 21 million tons of plastic annually consumed for packaging and nondurable goods, as well as divert the 16.7 million tons of plastic waste entering landfills. However, being derived from renewable resources does not guarantee that biopolymers will perform favorably when compared to petroleum-based polymers [16], and as such, sustainability assessments like LCA are conducted to compare and improve the environmental impacts of biopolymers.

This review presents a broad summary of the current status of environmental impact assessments for biopolymers. We begin with an overview of biopolymers and an introduction to life cycle assessment (LCA). Then we review the output data from the commonly used life cycle inventory (LCI) database, ecoinvent, and impact assessment tool. Finally, we review and analyze the findings of LCA studies on biopolymers that have been published within the peer reviewed literature.

2. Common biopolymers

The studies reviewed in this paper focused on the life cycle assessment (LCA) results of PLA, PHA, and thermoplastic starch (TPS). These are the most prevalent biopolymers currently represented in life cycle literature. While there are other biopolymers on the market and in development, such as bio-based 1,3-propanediol (PDO) and bio-based polyethylene terephthalate (Bio-PET), publicly available data and life cycle assessment results were not available at the time of this review.

The applications of PLA include clear and opaque rigid plastics for packaging, disposable goods, durable goods, and bottles, as well as films and fibers for a variety of purposes [17,18]. PLA is made from lactic acid, which is produced through the fermentation of dextrose typically sourced from corn, however any starch-rich feedstock could be used. Lactic acid can be polymerized in a number of different ways to create granules that are used to make commercial products [19–21]. PLA can be blended with petroleum-based polymers or fibers, either synthetic or natural, to improve the heat resistance or durability of the plastic [7]. PLA-based plastics can be biodegradable and compostable, features that offer a wider variety of options for disposal [22].

PHA had a short history of use in packaging and bottles but is not widely used in these applications today [22]. PHA is increasingly being used in more niche applications in a variety of industries from medicine to agriculture. PHA is produced through the bacterial fermentation of renewable feedstocks containing monomers such as glucose, sucrose, and vegetable oil, resulting in the formation of the polymer [23,24]. Similar to PLA, PHA can also be combined with other materials to form composites with improved properties. PHA is also biodegradable and can be used to create compostable plastics [24].

Another biopolymer included in the studies reviewed herein is TPS. It is created using the starch polymers from renewable sources, primarily corn, which is then processed and combined with additives and formed into shape [25]. TPS is generally incorporated into composites with synthetic polymers to create materials appropriate for the market. These materials can be used in making films, rigid materials, such as plates and cutlery, packaging, and foams, and, depending upon the constituents may be biodegradable and compostable. Current research efforts are focused on creating new TPS based composites by incorporating fibers or nano-materials to improve or completely change the characteristics of starch products [25–28].

Two other important plant-based materials in the polymer industry are bio-based 1,3-propanediol (PDO) and bio-based polyethylene terephthalate (B-PET); however these polymers are not well represented in the LCA literature and thus were not included in the subsequent review. PDO is made through biological fermentation processes in conjunction with petroleum products to create materials comparable with nylon. The primary biological feedstock used in the fermentation process is corn grain, which makes up 37% of the polymer by weight. The remaining content is derived from fossil-based products [29]. Current applications of polymers made with PDO include carpeting, apparel, and films, which are reported to outperform traditional petroleum-based materials [30]. B-PET, which is made from combining bio-based ethylene and other petroleum-based feedstocks, is most notably used in clear plastic bottles. The ethylene portion is made from corn fermentation similar to the corn ethanol process, and is then synthesized in the same manufacturing process as traditional PET. This results in a product identical to traditional PET that is recyclable but not biodegradable [31]. Efforts exist to create a completely bio-based PET product [32].

PDO and B-PET products should be evaluated in an ongoing basis, similar to PLA and PHA, to determine the environmental