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Review article

Sustainability assessments of bio-based polymers

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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.

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,

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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

impacts of these products. Additionally, as manufacturing methods are refined and additional biopolymers are created, future research will be needed to identify the impacts of these products and identify where improvements can be made.

3. Life cycle assessment as a method for quantifying environmental impacts

To determine the environmental impacts of a product or process, a LCA is often conducted. LCA provides a comprehensive and quantitative analysis of the environmental impacts of a product or process throughout its entire life cycle. LCA is a powerful and widely used tool for measuring the sustainability of an enterprise or concept and informing decisions with respect to sustainability and environmental considerations. Guidelines for conducting an LCA are defined by the International Organization for Standardization (ISO) 14040 series [33]. There are four main steps to an LCA according to ISO:

1 *Goal and Scope Definition* – defines the extent of the analysis including the goals and the system boundaries. The functional unit for the LCA is defined within this step. The functional unit describes a reference for what is being studied and how much or over what time frame (i.e. 1 kg plastic resin).
2 *Inventory Analysis* – documents material and energy flows that occur within the system boundaries, often referred to as Life Cycle Inventory (LCI).
3 *Impact Analysis* – characterizes and assesses the environmental effects using the data obtained from the inventory, often Life Cycle Impact Assessment (LCIA). LCIA expresses the LCI data in common terms, usually with respect to an equivalency factor, such as CO2-equivients for greenhouse gas emissions. Common LCIA categories include global warming potential, non-renewable resource depletion, eutrophication, ecotoxicity, acidification, ozone depletion, smog formation, and human health (e.g. carcinogens, respiratory impacts, and non-carcinogens).
4 *Interpretation* – reviews the results of the LCA, identifies opportunities to reduce the environmental burden throughout the product's life, and provides conclusions and recommendations.

Many organizations have established guidelines for performing detailed LCAs, including the Environmental Protection Agency (EPA), and the Society for Environmental Toxicology and Chemistry (SETAC) [33–36]. All of these organizations describe LCA steps similar to those listed above. Assessments can range from conceptual models to detailed quantitative analyses. There are a host of LCA software packages and tools available to aid in the construction of an LCA. Additional information is available in the further reading section of this chapter.

LCAs can be comparative or stand-alone (i.e. an analysis of a single product). Through use of a stand-alone LCA, it is possible to observe which stage (creation, use, or disposal) causes the most impact and may offer suggestions to minimize impacts throughout the product life. Comparative LCAs among possible products help to determine the environmentally preferable alternative.

The system boundaries of an LCA may extend from cradle to gate, cradle to grave, or cradle to cradle. As depicted in Fig. 1, cradle to gate (dashed lines) implies that the life cycle assessment covers activities prior to the use phase while cradle to grave (dashed and dotted lines) includes the product's use and end-of-life. Cradle to cradle (whole chart) indicates a product that can be disposed of and returned back to the natural environment; the life cycle of PLA can be considered as such because when PLA degrades its carbon is recycled back into the environment for uptake by biomass. In LCAs of polymers, practitioners may also describe boundaries from the

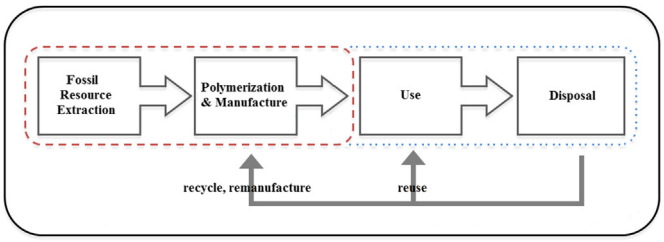

Fig. 1. Generic life-cycle stages for polymers. The dashed line indicates a cradle to gate system boundaries, the dotted line is an extension of that system boundary to cradle to grave, and the entire figure is indicative of a cradle to cradle assessment.

cradle to pellet; where the analysis stops at the creation of resin pellets, and excludes processes downstream including product manufacture, use, and disposal. Furthermore, LCA practitioners also refer the system boundaries in terms of 'scope'. The system boundaries for a scope 1 LCA would include only the material and energy flows associated with the manufacturer; for example, Scope 1 system boundaries for the polymer manufacturer would extend only to the direct inputs and outputs associated with their factory. Scope 2 system boundaries include Scope 1 in addition to all supply chain and raw materials extraction data. Scope 3 system boundaries are used to define the entire life cycle, including any further production or processing downstream of Scope 1 as well as use and disposal.

4. Review of environmental impacts of polymers reported in existing LCA databases

LCA data is readily accessible in existing LCA tools for some biopolymers and most petroleum-based polymers. To review the environmental impacts reported in these existing LCA databases, life cycle data for biopolymers and petroleum-based polymers were obtained from the ecoinvent v2.2 database [37]. LCA data is available within ecoinvent for high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and two biopolymers: PLA and TPS. This data is reported in ecoinvent by the "European plastics industry" for petroleum polymers, while biopolymer data is reported by NatureWorks for PLA compiled in 2007, and from Novamont from 2004 for TPS. In order to review and succinctly present the ecoinvent data (which otherwise would be tables of hundreds of material and energy flows), LCA software such as SimaPro enables LCI data from ecoinvent to be used in conjunction with the TRACI v2.00 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) [38], developed by the US EPA, to compare life cycle impacts from the database. TRACI calculates impacts for global warming potential (GWP), eutrophication, ecotoxicity, acidification, ozone depletion, smog formation, human health – carcinogens, human health – non-carcinogens, and human health – respiratory. The limitations to reviewing existing biopolymer LCI data in this manner are discussed in subsequent sections.

The comparative life-cycle environmental impacts from existing databases for petro- and biopolymers are shown in Figs. 2 and 3, reported directly from ecoinvent and TRACI with no modifications. These figures present a simplified analysis of the ecoinvent data using TRACI to demonstrate life cycle methodology, and can provide a baseline for the environmental impacts of PLA and TPS with commonly used data and tools. The results reported from ecoinvent represent a cradle to granule (i.e. gate) system boundary for the production of 1 kg of granules for the five common petroleum-based plastics and PLA. Since TPS is not formed into granules, the

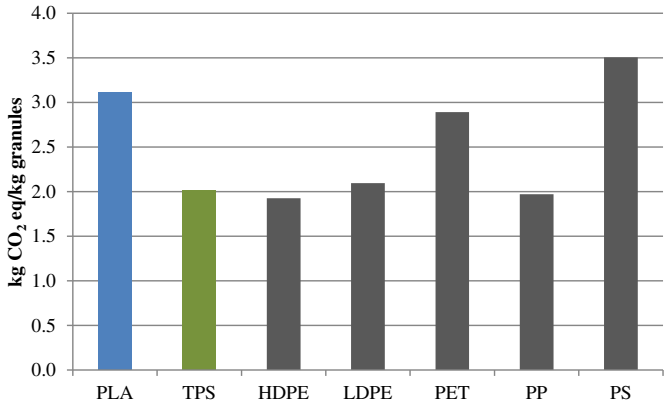

Fig. 2. Global warming potential for cradle to granule (gate) of PLA and TPS compared to five common petroleum-based plastics. Data taken from ecoinvent v2.2 and TRACI v2.00. PLA = polylactic acid, TPS = thermoplastic starch, HDPE = high density polyethylene, LDPE = low density polyethylene, PET = polyethylene terephthalate, PP = polypropylene, PS = polystyrene.

functional unit for TPS was 1 kg of processed starch. While the polymers are compared in Figs. 2 and 3 by weight, the functional units and thus the comparative impacts of the subsequent products may vary.

While Fig. 2 shows little difference between the biopolymers and petroleum-based plastics with regards to GWP, it is clear from the results of other impact categories included in Fig. 3 that there are environmental tradeoffs between biopolymer and traditional polymer production. There are environmental impact categories, notably eutrophication, ozone depletion, and non-carcinogenic human health, in which the biopolymers exhibit higher environmental impacts when compared to the petroleum-based plastics. However, the relative significance of these impacts should be evaluated to determine whether or not some impacts occur at such small rates that there is no real impact as a result of the production process. The significance of the impacts can be determined through normalization and weighting, which assigns weighted values to the different impact categories and helps compare them to known impact values. This review paper does not apply weighting or normalization to determine significance; the reader is referred to Development of normalization factors for Canada and the United States and comparison with European factors [39] for an example of normalization factors for TRACI.

Using LCI data combined with an LCIA tool in a black box approach as depicted in Figs. 2 and 3 may result in overestimation of impacts or even an inaccurate model of the system. Many environmental impact categories have certain conditions that must be modeled accurately. For example, in the case of the eutrophication category, water bodies tend to be either nitrogen or phosphorus limited, which means that only N compounds would contribute to eutrophication in N-limited water bodies. As such, P emissions would not contribute to eutrophication in those areas. When LCI data is analyzed using LCIA tools without customization, these details related to regional implications and limitations of water bodies are not taken into account in existing LCA tools. Thus, eutrophication impacts can be overestimated. Similarly, impacts related to smog tend to only manifest in urban areas. However, black box LCA tools do not account for regional variations in emissions, and again may overestimate the impacts of smog-related emissions. In the case of PLA, smog related emissions occur primarily at power production facilities (40%) and on farms (33%); farms in particular are generally located where they are less likely to contribute to smog. When conducting a comprehensive LCA of specific products with known production locations and known supply chains, it is important to understand and model the particulars of the system, while simultaneously utilizing sensitivity analysis and scenario analysis to determine any changes to LCA impacts resulting from changes to supply chains or production facilities.

Based on the outputs from TRACI and the data supplied by ecoinvent, the eutrophication attributed to the biopolymers is due in large part to agricultural N and P emissions from intensive farming, which contributes 52% of the eutrophication impacts for PLA and 56% for TPS. Energy use during the production process was the secondary driver of eutrophication for biopolymers. Eutrophication from PET production results primarily from the use of ethylene and ethylene glycol, which is one of the primary compounds used to make PET (with either dimethyl terephthalate (DMT) or terephthalic acid (TPA)). Biopolymers' ozone depletion impacts are largely attributable to emissions that result from the transport of fossil fuels used in the process of creating the biopolymers. The non-carcinogenic human health impacts from TPS can be associated with the ecoinvent data for intensive corn farming in Switzerland which results in zinc emissions to the soil. TPS exhibited more than 7 times greater noncarcinogenic human health impacts compared to PLA, which are both made from corn. A sensitivity analysis was performed to determine if the methods of farming defined by ecoinvent were impacting the results. Ecoinvent data for PLA is derived from average corn production occurring in the US while ecoinvent data for TPS corn production is from Switzerland [37].

In order to evaluate the difference that the ecoinvent regional agricultural data has on resultant LCA environmental agricultural impacts, the original ecoinvent TPS results were compared to a modified TPS process that was built using the PLA corn agricultural data. Only the agricultural data was changed in the modified TPS process; and all data was obtained without modification from ecoinvent. Similarly, an additional sensitivity analysis was conducted to determine the effects of different electricity mixes between the TPS (ecoinvent utilizes Italy's mix) and PLA (ecoinvent uses a generic European mix) ecoinvent data. The results of the sensitivity analysis can be seen in Fig. 4. This sensitivity analysis demonstrates minimal change due to the electricity mix. However, the effect of the data from ecoinvent's regions for corn production created dramatic effects on the results for non-carcinogens that would bring the non-carcinogenic human health impacts for TPS down to 1.99E-7 CTUh, falling between PLA and PET. When we reviewed the inventory data in ecoinvent we found that corn produced in the US resulted in negative zinc emissions, while corn grown in Switzerland results in zinc emissions to the soil. This is a discrepancy in the data that is characteristic of the types of problems that can manifest in LCA results if LCI data is not evaluated and properly validated.

When taken together, Figs. 2 and 3 make it difficult to determine if there is a significant difference between the cradle to gate production of biopolymers and petropolymers. Some LCAs attempt to answer this question through a normalization process to show whether or not different impact categories are significant. With ecoinvent system boundaries only from cradle to granulate (or kg of starch in the case of TPS), biopolymers do not exhibit a clear win or lose across any of the environmental indicators when compared to petroleum polymers. It is not clear that PLA and TPS are 'better' or 'worse' within the acidification, smog formation, ecotoxicity, carcinogen or respiratory categories. PLA's ecotoxicity impacts range from 3 times greater than PP and only 1.2 times greater than PET. However, PLA and TPS result in higher eutrophication and ozone depletion impacts than their petroleum counterparts. Finally, TPS non-carcinogenic human health impact results from ecoinvent and TRACI may be overestimated by a factor of four as described in the sensitivity analysis.

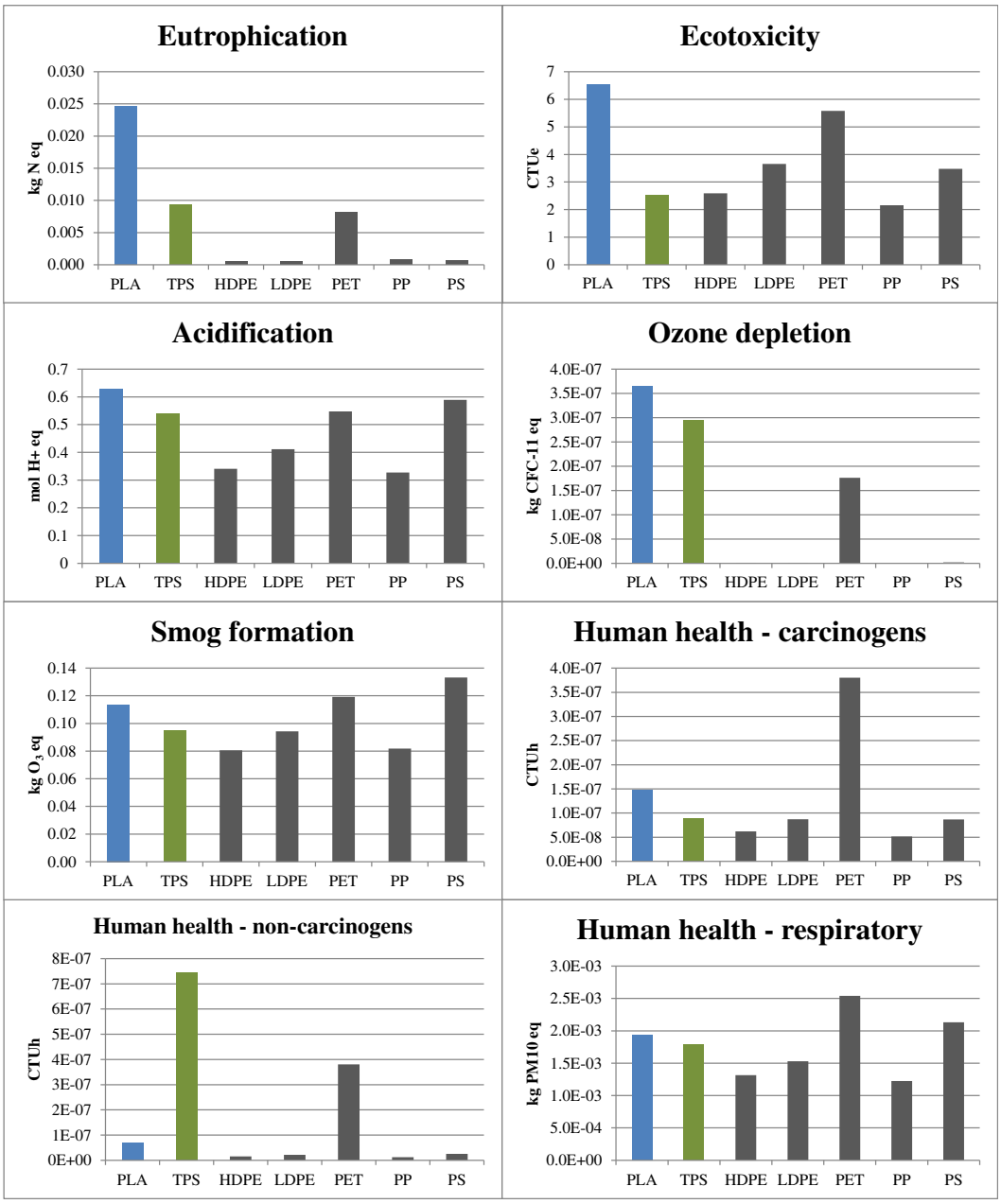

Fig. 3. Life cycle environmental impacts of PLA and TPS compared to petroleum-based polymers per kg of granule (starch). Data taken from ecoinvent v2.2 and TRACI v2.00. PLA = polylactic acid, TPS = thermoplastic starch, HDPE = high density polyethylene, LDPE = low density polyethylene, PET = polyethylene terephthalate, PP = polypropylene, PS = polystyrene. CTUe = Comparative Toxic Unit ecosystem, CTUh = Comparative Toxic Unit human health.

5. Review of published LCAs

Table 1 summarizes LCAs of biopolymers published in the peer-reviewed literature through 2012. The environmental performance of PHA, PLA, and TPS has primarily been evaluated from the cradle to the production of resin or pellet with fewer than half of the studies including EOL in the system boundaries (Table 1). The studies compare biopolymers to petroleum-based polymers on the basis of GWP and nonrenewable energy use, while other EPA criteria air pollutants and nonpoint aqueous emissions are included in only a few of the studies. Fig. 5 summarizes the distribution of environmental impact areas that were evaluated in recent biopolymer LCAs. Of the twenty-one studies reviewed, nearly all of them evaluated GWP and energy use, while other areas of impact were largely ignored with fewer than 25% of the studies evaluating ecosystem quality, eutrophication, human health, land use, or water use. The emphasis is clearly on greenhouse gas emissions and energy use. LCAs that assess only GHGs and nonrenewable energy consumption may miss potential unintended consequences resulting from switching from petro to biopolymers. For example, bio-based products have been shown to exhibit tradeoffs in the form of decreased greenhouse gas emissions while experiencing increased water quality degradation [16]. Biopolymers may outperform petroleum-based polymers, but that cannot be confirmed unless LCA practitioners are creating clear assessments of the environmental impacts of both petroleum-based polymers and their bio-based counterparts.

The LCAs summarized in Table 1 run the gamut in regards to system boundaries, research goals, product types, assumptions,

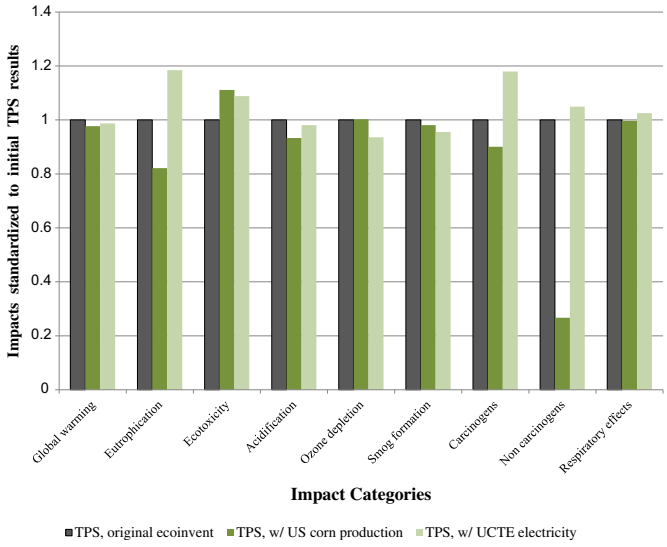

Fig. 4. Sensitivity analysis for the corn production and energy mix of TPS using the TRACI v2.00 results and data from ecoinvent 2.2 database. TPS original ecoinvent uses German corn production and an Italian electricity mix. TPS w/US corn production swaps TPS original ecoinvent agricultural data with US corn production data used in ecoinvent PLA data. TPS w/UCTE electricity swaps TPS original ecoinvent electricity data with ecoinvent electricity data for PLA processes, which were derived from Union for the Coordination of the Transmission of Electricity averages.

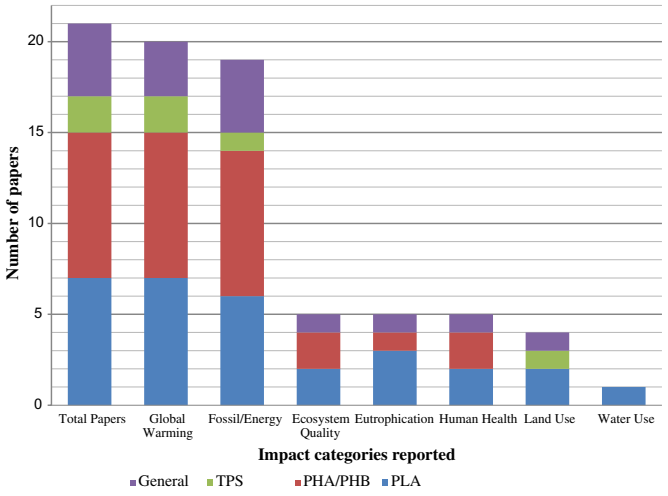

Fig. 5. Impact categories included in peer reviewed biopolymer LCAs. 'General' refers to studies that looked at biopolymers in general without focusing on TPS, PHA, or PLA.

and EOL scenarios. These are important differences that help to explain the variability of the results and determine which studies should inform the larger debate. A majority of the LCAs were conducted to evaluate specific products, such as PLA [18,40,42,45,47,49–51,53,55]. Other studies focused primarily on the manufacturing process [23,46,48,52], the types of feedstocks being used [43,44,54], the overall sustainability of the polymers [8,22], the compostability of products made from biopolymers [41], or the land use change associated with the production of biopolymers [56].

Similarly, when the system boundaries extended to the product or end-of-life, there were significant differences in the types of products assessed; Heyde, James, and Piemonte looked at plastic bags [42,51,56], Bohlmann and Madival looked at containers for food [50,53], and Shen assessed generic packaging [55], all of which would be considered non-durable goods or packaging. The study by Pietrini looked at monitor casings and car panels and was the only LCA reviewed that evaluated durable goods [45].

The remaining figures are related to GWP reported for the biopolymers in these studies. Aside from greenhouse gases being significant factors in the environmental impacts of a product, GWP was the most consistent measure used in the studies and for which most of the data could be converted to a single unit of measure for comparative purposes. Of the twenty-one studies, fifteen reported data that could be used in the subsequent comparisons.

Fig. 6 illustrates the range of reported CO_2 equivalents among fifteen LCAs published over a twelve-year period. Of the twenty-one studies, fifteen reported data that could be used in these comparisons, while the remaining six did not report in values that could be converted to CO_2 equivalents. Study (f), (l), and (n) provided single data points while the others provided ranges due to scenario changes and uncertainty. Fig. 6 also illustrates the overall range of CO_2 equivalents reported among the reviewed LCAs of biopolymers that included greenhouse gases in their life cycle inventory. The TPS data was sourced from a limited number of studies and does not indicate a very broad range.

Table 1
Impact categories and system boundaries of previous biopolymer LCAs. Studies include: [8,18,22,23,40–56]. End of life (EOL) scenarios: I = incineration without energy recovery, IR = incineration with energy recovery, L = landfill without methane capture (*indicates the study assumed no methane production), LC = landfill with methane capture, R = recycle, T = litter, C = compost .

Study Details			Life Cycle Impact Assessment Categories Reported							System Boundaries, Cradle to . . .			
Author	Date Accepted	Product	Global Warming	Fossil Fuels/Energy	Ecosystem Quality	Eutrophication	Human Health	Land Use	Water Use	Resin	Pellet	Product	EOL
Gerngross	August 2000	General		■						■			
Dornburg	July 2003	General	■	■				■		■	■	■	I
Kijchavengkul	Februrary 2008	General	■	■						■			
Tabone	September 2010	General	■	■	■	■	■			■	■	■	
Heyde	July 1997	PHB	■	■						■	■	■	I, L, R
Kurdikar	July 2000	PHA	■	■						■			
Akiyama	November 2002	PHA	■	■						■	■		
Kim	June 2004	PHA	■	■	■	■	■			■			
Pietrini	April 2007	PHB	■	■						■	■	■	IR
Yu	July 2008	PHA	■	■						■			
Zhong	November 2008	PHA	■	■	■		■			■			
Kendall	January 2012	PHB	■	■						■			
Vink	November 2002	PLA	■	■					■	■	■		
Bohlmann	November 2004	PLA	■	■						■	■	■	L*, LC
James	June 2005	PLA	■			■				■	■	■	C, LC, R, T
Vink	April 2007	PLA	■	■						■	■		
Madival	March 2009	PLA	■	■	■	■	■	■		■	■	■	IR, L*, R
Vink	June 2010	PLA	■	■						■	■		
Groot	July 2012	PLA	■	■	■	■	■	■		■	■		
Shen	May 2008	TPS	■	■						■	■	■	IR
Piemonte	December 2010	TPS	■					■		■	■	■	

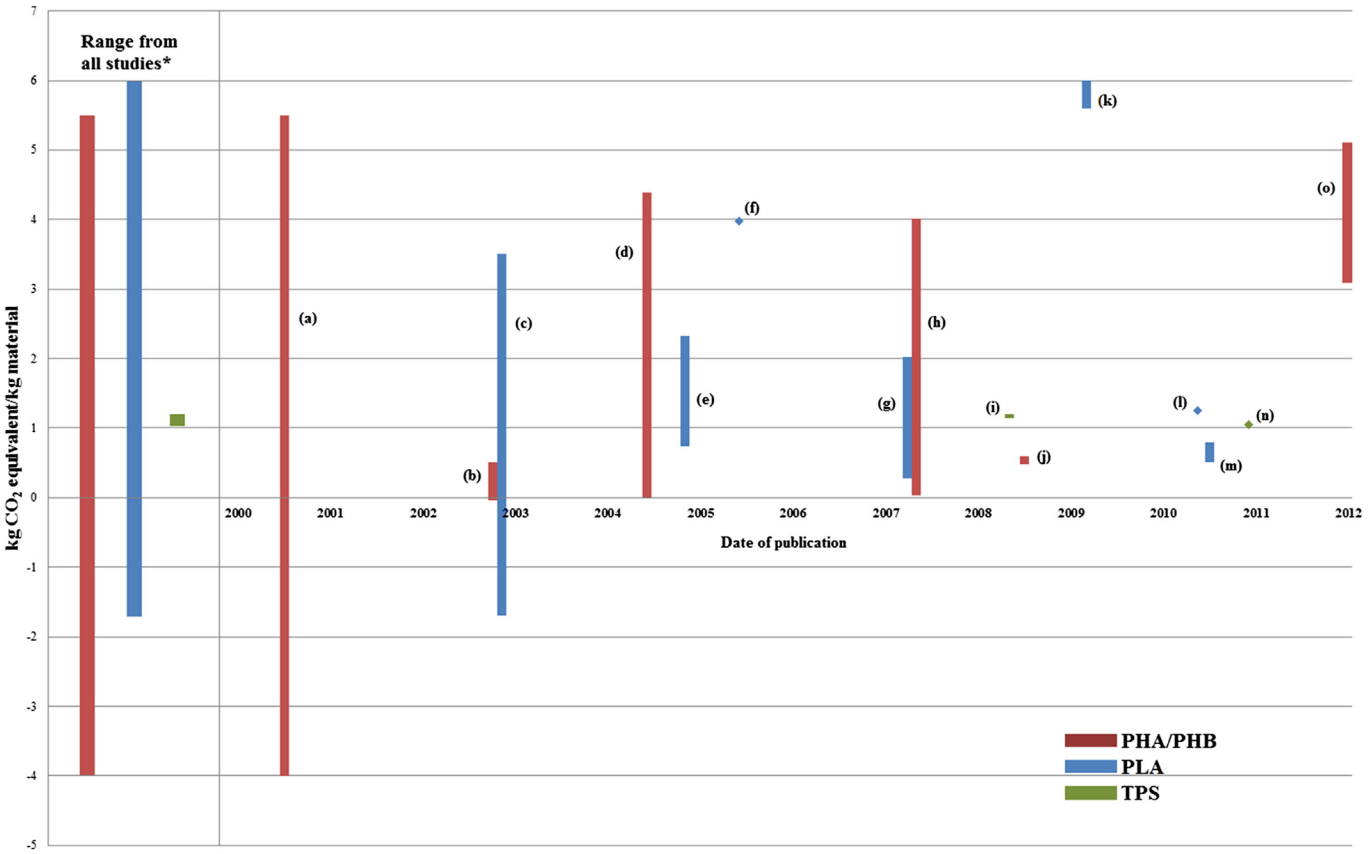

Fig. 6. Reported LCA ranges of CO_2 emissions equivalents for PHA, PLA, and TPS from the reviewed studies. *Each study had different system boundaries and scenarios that contributed to this range. (a) Kurdikar [43], (b) Akiyama [23], (c) Vink [49], (d) Kim [44], (e) Bohlmann [50], (f) James [51], (g) Vink [52], (h) Pietrini [45], (i) Shen [55], (j) Yu [46], (k) Madival [53], (l) Vink [18], (m) Groot [54], (n) Piemonte [56], and (o) Kendall [48].

The system boundaries and assumptions within the studies significantly influence the GWP results reported in Fig. 6. For example, transportation emissions and EOL scenarios in Madival's study (k) resulted in significantly higher GWP numbers than the other LCAs of PLA that omitted these emissions.

Likewise some of the lower values reported can be attributed to the use of alternative energy scenarios in the LCAs; this is particularly visible in two studies by Vink (c, g) and the one by Groot (m). Vink's use of wind power and renewable energy certificates (RECs) in some scenarios results in the lower range of GWP reported for the biopolymers [49,52]. Vink's most recent paper does not incorporate wind energy offsets in this way [18]. Similarly, the study by Groot (m) includes carbon offsets from burning left over biomass for energy, reducing the GWP of PLA by offsetting the need for fossil fuels in the manufacturing process [54].

Kurdikar's wide range of findings for PHA (a) are a result of divergent scenarios that assume single source heat and power generation with biomass power resulting in net negative carbon emissions. Kurdikar's coal scenario topped out the charts with around 5.5 kg CO_2 equivalent per kilogram of PHA [43]. Kurdikar's early study reports both the upper and lower limits in Fig. 6 for the LCAs of PHA/PHB. The later studies, able to refine their scenarios and system boundaries, provided greater certainty with their results.

The system boundaries of the studies and which EOL scenarios, if any, were included in the LCA can greatly influence the GWP results, which is explored in more detail in Fig. 7. Fig. 7 depicts the average of the fifteen studies included in Fig. 6, breaking them up based on the system boundaries used in the LCAs. Though the EOL scenarios are different in each LCA, Fig. 7 demonstrates that when EOL is included in the system boundaries of an LCA for PHA and PLA, the GWP of the products increases up to 12-fold and 6-fold from the pellet, respectively. Table 1 shows that three of the LCAs

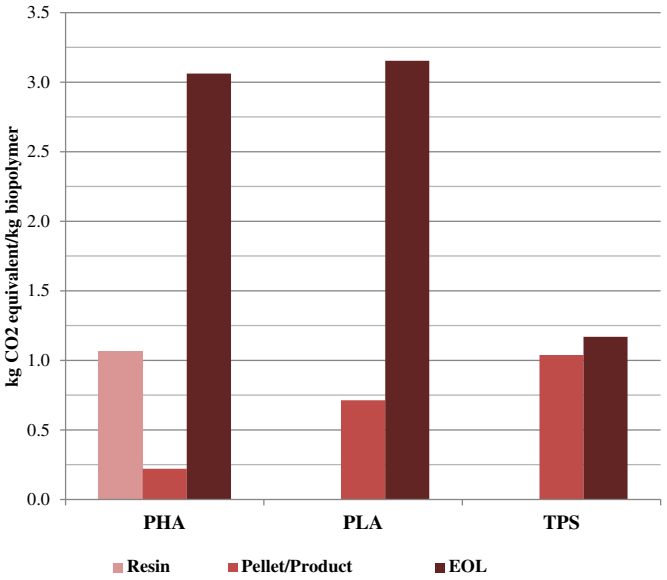

Fig. 7. Average global warming potential of biopolymers based on the extent of the system boundaries of the fifteen different LCAs [18,23,43–46,48–56].

included only one method of disposal while the other four studies evaluated two or more methods of disposal. Furthermore, methane capture or lack thereof during landfill scenarios [57] and uncertainty regarding composting methods, which may include too much moisture or not enough oxygen leading to methane emissions [49], may also drastically affect the greenhouse gas emissions from the biopolymers.

Including EOL provides a more comprehensive estimate of the life-cycle environmental impacts of biopolymers. However, the specific method of disposal may also provide varied results. In fact, despite the compostability of many biopolymers, the predominant method of plastics disposal in the US is recycling or landfilling. Few US cities have compost infrastructure. A sensitivity analysis of EOL studies is important to ensure the results do not hinge on a single assumption, especially when the assumption is based on consumer behavior. Additionally, the scenarios must be representative of how the biopolymers are being disposed of or viable alternatives. Madival provided a nice example of scenarios for comparison: Scenario 1) 40% recycling, 30% incineration, 30% landfill, Scenario 2) 100% landfill, Scenario 3) 100% recycling, Scenario 4) 50% incineration, 50% landfill, and the Current Scenario for the US – 23.5% incineration, 76.5% landfill [53]. These scenarios provide a wide variety of EOL combinations in order to explore the upper and lower limits of the impacts that result from the different methods of disposal.

6. Summary

Life Cycle Assessment is a tool that can quantify the environmental impacts of biopolymers. However, the environmental impacts associated with the creation, use, and disposal of biopolymers remains unclear, since biopolymers can be made into a variety of products for a variety of uses, and ultimately are disposed of in many different ways. One role of LCA practitioners is to identify current production benchmarks and to analyze future scenarios to help guide the development of manufacturing, use, and disposal for sustainable products.

There are other factors and tradeoffs that are important to the life cycle environmental impacts of biopolymers beyond a simple cradle to gate LCA study. The end-of-life options for biopolymers may prove to alter the product's environmental profile. The general assumption is that biopolymers quickly degrade and recycle their carbon to other plants via biological recycling. However, recommendations for waste management of PLA state that the material should be composted at *industrial facilities* since the appropriate degradation conditions cannot be met in the typical 'backyard' compost pile [17,58,59]. Industrial composting may add additional cost and transportation dimensions to the disposal of compostable products that make composting more comparable to a landfilling scenario which may further decrease any GWP benefits that were achieved. Despite the ability to compost most biopolymers, landfilling is currently the dominant waste management method in the US, and a major effort would be required to change personal disposal habits, including education of consumers and infrastructure for composting [60–62]. While PLA has been shown to be stable in landfills [63], landfilling may alter the environmental profile of other biopolymers with the potential for methane emissions and uncertainty surrounding the capture of landfill gas [57].

Biopolymers can be made to be biodegradable and compostable, but most US cities do not have composting infrastructure. The LCA by James [51] was the sole study that included composting as an EOL option. This highlights a major discrepancy between the feature of compostability and LCAs that simply analyze current polymer disposal practices rather than exploring the potential of creating new waste management pathways that may provide future environmental benefits or unintended negative consequences.

Little work has been done to assess the recycling options for biopolymers using LCA methodologies. It has been shown that of the different disposal options for petroleum-based products, recycling offers substantial environmental advantages over other alternatives [60,64]. However, proper labeling and handling procedures for recycling facilities will be needed to ensure that biopolymers do not foul other recycling streams. Recycling may provide other life-cycle benefits by reducing feedstock requirements and energy input [65]. However, similar to composting, the current infrastructure and logistics required may be a barrier to recycling of certain biopolymers like PHA and PLA. As noted by Song and colleagues, "although it is feasible to mechanically recycle some bioplastic polymers such as PLA a few times without significant reduction in properties, the lack of continuous and reliable supply of bioplastics polymer waste in large quantity presently makes recycling less economically attractive" [66]. While this is a problem with a number of recyclable materials, as the biopolymer market continues to grow it may eventually became economically feasible to recycle biopolymers, which in turn could have a beneficial impact on the environmental performance of these products. Organic contamination caused by the use of biopolymers in food packaging further complicates the recycling of biopolymers [67], but the ability to compost them provides alternative waste management strategies when compared to traditional plastics. The optimal disposal scenario could involve incineration, composting, recycling, landfilling, or a combination of the aforementioned alternatives and may be different depending on the type of biopolymer.

Many of the EOL scenarios reported in the literature are based on typical MSW ratios for plastics, but with most disposable biopolymers being advertised as compostable, it is unclear how consumers are disposing of these biopolymers. In addition, it is not clear what mix of EOL scenarios would provide the greatest benefits to biopolymers' life-cycle environmental impacts. While there have been studies clearly stating that biopolymers will not break down under landfill conditions, particularly PLA [41,53,59,63], others still report methane emissions from landfilling as an impact in the life cycle for these products [42,50,51,54,55], thus increasing the GWP associated with biopolymers. Scenario development and sensitivity analyses can help identify where assumptions such as methane emissions from landfilling of biopolymers have significant impacts and in what areas additional research is needed to provide more accurate data for the LCA.

It is important for LCA practitioners to present transparent data and assumptions and to provide the necessary context of their findings in order to accurately quantify the impacts from biopolymers and traditional plastics as well as to aid the industry in making effective improvements. Databases, while convenient, must be scrutinized for accuracy and completeness. As production methods change, updates to inventories must be made. For example, Vink has continued to provide updated profiles for the creation of NatureWorks' PLA which should be incorporated into any future LCAs of that product [18]. The quality of LCA findings is not only a function of determining appropriate system boundaries but is also determined by the quality of the inventory data. The ecoinvent database with TRACI produced results that were not commensurate with the results from NatureWorks [18], as described in the review of environmental impacts of polymers. These types of discrepancies result from a wide range of variables, namely differences in system boundary selection, in methods of calculation for environmental impacts, and the quality of the inventory data. All of these factors and assumptions can influence resultant impacts like GWP which, depending on system boundaries, may exclude carbon uptake by plants or ignore the GHG emissions that result from end of life treatments. Further, the

environmental impacts of polymer production estimated in peer-reviewed LCAs are not consistent throughout the literature. Exploring the impacts of the polymer industry will help determine which impacts are relevant to the discussion and those that prove to be insignificant.

The potential benefits of biopolymers in regards to GWP will not be realized until the material and energy demands from the farming and production processes are reduced. The use of REC's in Vink's 2003 and 2007 studies of PLA demonstrate the power of a low fossil fuel energy paradigm combined with carbon negative feedstocks [49,52]. There is a great potential to sequester atmospheric carbon into everyday material. As noted by Gerngross and Slater, "any manufacturing process, not just those for plastics, would benefit from the use of renewable energy" [22]. The mitigation of the other environmental impacts, such as water quality degradation from agricultural practices, will further enhance the environmental profile for biopolymer products.

Biopolymers are relatively new to the market when compared to their petroleum counterparts. The industry has made significant gains over a short period of time [17,18,49,52], and any comparison between biopolymers and fossil-based polymers must take these technology improvements and productivity into account. The fact that biopolymers are currently on par with traditional plastics means that further technology improvements and economies of scale have the potential to tip the scales in favor of biopolymers. Environmental impacts resulting from agricultural production will need to be managed in order to maintain and improve any benefits gained by transitioning to bio-based production. Better agricultural nutrient management practices or the development of new feedstocks that require minimal energy and nutrient inputs are two ways to improve the impacts from agriculture [12,68]. Taking a whole-systems approach to designing sustainable biopolymers will lead to a path of biopolymers with clear life cycle environmental benefits compared to their petroleum counterparts. However, without a clear understanding of the distribution for biopolymers in waste streams, the resultant cradle to grave life-cycle environmental impacts of biopolymers remain uncertain. Life cycle analysis will continue to be a useful tool to identify more sustainable methods of production, use, and disposal of biobased products.

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