LCA of PHA Production – Identifying the Ecological Potential of Bio-plastic

M. Narodoslawsky,* K. Shazad, R. Kollmann, and H. Schnitzer
Institute for Process and Particle Engineering, Graz University of Technology, Inffeldgasse 13/3, 8010 Graz/Austria

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Review
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A major reason for the call to increasingly switch towards polymers based on renewable resources is their presumed advantage regarding ecological performance compared to fossil competitors. Usually, this argument is based on the assumption that products based on renewable sources hold an inherent ecological advantage over products derived from other sources, in particular fossil sources. This claim however must be substantiated by looking into the ecological impacts accrued by the production of a material along the whole life cycle, from the raw material generation to the provision of the final product. Only thorough life cycle assessments (LCA) can provide solid, comprehensive and quantifiable information about the ecological performance of products, and thus answer the question of any superiority of bio-polymers regarding their environmental impacts.

The paper will review the ongoing discourse about environmental performance of PHA in literature. It will also analyse the most important factors that decide about the ecological performance of PHA derived from different raw materials as well as the potential for improvement that is still available for PHA production.

Key words:
LCA of bio-polymers, ecological performance of PHA, LCA applied to process development

Introduction

The issue of environmental performance of bio-plastics has attracted a large number of researchers over the last two decades. This is a natural result of the fact that bio-plastics have an intrinsic economic disadvantage compared to fossil-based polymers due to higher raw material costs, production processes still in relatively early stages of technical development, and smaller production units, giving fossil competitors the advantage of the economy of scale. Market introduction of bio-polymers therefore requires advantages in other fields to compensate for this, and as long as fossil resources are still available at reasonable prices, ecological performance is a logical argument for bio-polymers in general.

A thorough review of the numerous publications that evaluate the ecological performance of bio-polymers from the PHA family, often in comparison to fossil competitors, is out of the scope of this paper. Already, there is a number of meta-studies about LCA publications on PHA production, which will form the backbone of arguments in this paper regarding the discourse about ecological performance of PHA. More than just giving an overview on all these publications, the intent of this contribution is to provide the reader with background information on how to find a pathway through the controversial results of such studies. In addition, the paper will analyse the most important aspects of the PHA life cycle.

Diversity of approaches leads to diversity of results

Almost all studies, except those written in the mid-1990s, will use Life Cycle Assessment (LCA) methodology for assessing ecological performance of PHA and competing materials. This methodology is standardised by the International Standardisation Organisation (ISO) in the 14.04x series of ISO standards[1]. This standardisation, though extremely helpful, still leaves considerable space for conducting a particular evaluation. It prescribes structure and content of LCA studies and provides rules for defining the life cycle and the evaluation itself, but reserves crucial decisions to the authors of the studies. This leads to the situation that LCA studies published about the same issue (e.g. ecological performance of PHA vs. fossil and bio-based competitors) do not lead necessarily to the same results[2]. This situation is quite obvious when surveying different reports about LCA of PHA.

One reason for diverging LCA results is the difference in normative foundations of the measures applied. Any ecological evaluation method inherently needs a normative orientation as it measures

*Corresponding author: e-mail: narodoslawsky@tugraz.at

what is seen to be positive or negative with regard to environmental pressures exerted by the production of a good. There is still no universally accepted ecological norm available, and so any LCA consequently provides a judgement relative to the normative base of the evaluation method it applies. In many cases, LCA studies may draw on problem-oriented indicators[3] such as Global Warming Potential (GWP) or Acidification Potential. In other cases, the evaluation will be based on Carbon Footprint[4] or Water Footprint[5]. These indicators rate the environmental pressures of life cycles according to particular environmental problems, using either a reference impact or a desired state of the environment as a benchmark. It must be noted that the selection of this benchmark itself, already constitutes a normative step that is either derived from a certain vision of what constitutes a preferable state of the environment, or what pathway human development in relation to nature should take, or what particular change in nature is undesirable. As these visions differ quite markedly in society, so do the results of LCA studies based on them.

Some LCA studies may use a combination of a number of such indicators. Although this usually provides a more comprehensive picture of the environmental impact of product life cycles, it also blurs the results as indicators may point to different directions.

A way to overcome this problem is to use a number of indicators and weigh them, or to apply highly aggregated measures such as Emergy[6] or the Sustainable Process Index (SPI)[7], a sort of ecological footprint. In these cases, the weighing method or the way the aggregation of different ecological pressures is performed, is again based on normative assumptions.

The differences in the normative basis of evaluation methods applied in LCA studies will lead to different results, even if they use exactly the same eco-inventory, i.e. the same process limits and the same mass and energy balances for the whole life cycle. In practice, however, neither process limits nor eco-inventories are usually exactly the same across different LCA studies. Even if the resources and processes may be the same, different ways of providing electricity and process heat will have a profound impact on the result of the LCA studies.

In many cases, the functional units used in LCA studies differ: some may assess a unit of material while others may be applied to compare goods (e.g. plastic bags) produced from competing materials. As these goods may have different weight when produced from different materials, because of dissimilar physical properties, such LCA studies of goods may have different results than LCA studies comparing the materials themselves.

There is a feature of bio-polymers that contributes in particular to diverging results of LCA studies: in contrast to fossil-based polymers, bio-polymers can be produced from a wide variety of raw materials, from prime agricultural crops like corn, sugar beet or sugar cane to by-products from other industries, like slaughter house residues and whey, to outright waste flows like activated sludge from wastewater[8]. It is therefore only natural that one cannot expect a clear-cut result from LCA studies of bio-polymers with regard to their life cycle environmental performance, how they compare among each other, and not even if they are inherently more ecologically benign than their fossil-based counterparts.

Review of LCA studies on PHA production

The following short review on LCA studies shall highlight the diversity of the discourse on ecological performance of PHA production. It is not comprehensive in the sense that it covers all published studies, but the sample is chosen to show, on the one hand, the different approaches to LCA in this field, and on the other hand, the diversity of results that are obtained from these studies.

In a classical meta-study published in 2005, Patel *et al.*[9] compared 20 LCA studies about various bio-based polymers and natural fibres, among them five about PHA. The studies show mixed results for total energy requirement (cradle to gate), depending on raw materials (starch, sugar beet) and the production (including PHA grown in genetically modified corn). This can vary from 10 % better than fossil-based high-density polyethylene to dramatically worse (by a factor of almost 8). Similar results can be obtained for CO_2 emissions from the life cycle. The authors, however, point out that these studies capture an early stage in the development of PHA production, both using fermentation and modified plants as well. They also point out that there was still a large margin for optimisation and that the use of bio-energy in the production process may well be the decisive factor of reducing ecological pressures of PHA production well below those of competing fossil polymers. Compared to other bio-based materials, however, PHA, according to this study, is less advantageous with regard to greenhouse gas emissions and energy requirements.

A more recent meta-study by Essel and Carus[10] published in 2012 based on 30 LCA studies of LCAs for PHA and polylactides (PLA), provides a more positive picture of PHA life cycle impacts. While the studies covered in this publication still show a large variation in the ecological indicators chosen for comparison (GWP in kg $CO_{2,equ}$ kg^{-1} of PHA and depletion of fossil resources in MJ kg^{-1} PHA), they generally perform better than fossil counterparts: PHA production will emit between –2 to +2 kg $CO_{2,equ}$ kg^{-1} of PHA and will consume from 2 to 70 MJ kg^{-1} PHA of fossil resources, fossil-based competitors will range between 2 and 8 kg $CO_{2,equ}$ kg^{-1} of PHA and between 75 and 110 MJ kg^{-1} PHA. Compared to PLA, PHA, according to this study, has about the same upper limit in both GWP and fossil resource depletion, but has a considerably lower bound on both measures. Compared to polypropylene (the fossil-based polymer with the lowest overall life cycle impacts), PHA can save on average 2 kg $CO_{2,equ}$ kg^{-1} in GWP and around 30 MJ kg^{-1} of fossil resources. The savings almost triple in both measures when compared to polycarbonates, the worst fossil-based material covered in this study.

Tabone *et al.*[11] compared in 2010 twelve polymers of fossil and biological origin, among them PHA from corn stalks and corn grain. This study is insofar of great interest, as it uses a wide range of problem-oriented ecological indicators like acidification, carcinogens, eutrophication, eco-toxicity, GWP, ozone and fossil fuel depletion. While it states the superiority of most bio-based materials (and PHA from corn stalks in particular) in GWP, it shows that they still have other impacts where they perform equally or even worse than many fossil-based materials. PHA from corn grain even tops the impact list in acidification by far, and both PHA from corn stalks and grain have a larger ozone depletion potential than fossil-based polymers, and are on par with or worse than polyethylene, polycarbonates, and polypropylene in eco-toxicity. Many of these impacts are, however, caused by the agricultural production of the raw materials.

A similar conclusion can be drawn from a study by Kim and Dale[12] who analysed the energy and GWP profiles of PHB from corn grain. They found PHB to have lower ecological impacts than fossil-based polymers, but pointed to the fact that sustainable practices in corn cultivation (no-tillage, winter cover) could further reduce the impact of PHB production by as much as 72 %.

Other studies have directly compared products from PHA with regard to their ecological impact. Here the differences in the (physical) properties of the materials come to play, as does the logistics linked to the production chain, as well as the use phase of the products. A study[13] compared PHB applied in CRT monitors (replacing of high-impact polystyrene, HIPS) and internal car panels, conventionally produced of glass fibre-filled polypropylene. In the case of monitor housings, PHB with either montmorillonite or sugar cane bagasse filling showed dramatic advantages to the conventional material, with only around 1 % of the GWP, and even lower impacts regarding non-renewable energy use. In the car panel application, however, the larger weight of the PHB-based compounds led to higher life cycle impacts, as fuel consumption in the use phase of the car increased. The best PHB-based material providing comparable service therefore had only savings of around 6 % in non-renewable energy use and 3 % in GWP.

Khoo *et al.*[14] compared polypropylene carrier bags produced in Singapore to PHA bags imported from US, using GWP, acidification and photochemical ozone production as measures. Using the US electricity mix, the PHA bags had a 69 % higher ecological impact than the PP bags produced (and used) in Singapore. Using electricity from coal, these impacts were even higher by a factor of 5! Only when using natural gas fired power stations as electricity source the impacts were on par with PP bags produced locally. When using clean (geothermal) energy as source for electricity, the impact of the PHA bags from the US, however, can be reduced to 20 % of that exerted by the production of PP bags in Singapore. This again highlights the paramount importance of the origin of energy in the life cycle of bio-based materials in general and PHA in particular.

Using LCA as guidance in development of PHA production processes

The diversity of results from different LCA studies must not distract from the fact that LCA is a powerful tool for guiding technological development. This is especially true for technologies that still require optimisation as a LCA can pinpoint "ecological hotspots", i.e. process steps and resources that cause high contributions to the overall life cycle ecological impact. PHA production processes with their wide variety of different raw materials, production schemes, as well as the different context they might be realised in, are excellent examples for this application of LCA.

Koller *et al.*[15] recently published an LCA study on a process utilising whey as a raw material for PHA production, using data from a 0.3 m^3 pilot plant to describe the optimisation requirements to make this process ecologically competitive to current fossil-based competitors, in particular polypropylene. Whey is a typical industrial by-product that requires further treatment to become a marketable product in any case. So they expanded their comparison also to competing treatment of whey to generate whey powder that may then be sold. Using a by-product as source for PHA production also minimises the impact from the raw material pre-chain, giving PHA from such sources an LCA head start.

The Sustainable Process Index (SPI)[7] was used in this study as ecological evaluation method. This is a highly aggregated measure that aggregates impacts from resource use and emissions, as well allows to unequivocally compare the ecological performance of different technological alternatives.

Using the raw data from the pilot plant to form the eco-inventory, PHA from this process is at a clear disadvantage to fossil competitors, showing an aggregated ecological footprint of 10.433 $m^2 kg^{-1}$ PHA compared to 1.726 $m^2 kg^{-1}$ for polypropylene. Closer inspection of results revealed that the major contribution to this large footprint comes from the use of electricity (based on the EU electricity mix). Eighty-eight percent of the ecological pressure of the fermentation step, and 79 % of the impact of the whole cradle to gate life cycle could be attributed to electricity input.

Pilot plants are, however, not industrial production systems, they are meant to gain experience for further optimisation of processes. In this case, two pathways for optimisation could be identified: increasing the yield of PHA from whey lactose (and thereby the amount of product generated by fermentation), and decreasing the energy demand for the fermentation step itself. Using experiences from other PHA production processes, the impact of these two optimisation measures were estimated. When combined, both optimisation measures would reduce the footprint per kg of PHA so that it is competitive with polypropylene on a mass base.

In this optimised process, transport from local dairies to central PHA production plant becomes important. A drastic optimisation can be achieved by concentrating whey at local dairies to the level used in the PHA production plant. This reduces the mass to be transported by almost 80 %, reducing the ecological footprint of PHA even further, to 1.455 $m^2 kg^{-1}$. This would reduce the ecological footprint of PHA from whey to 81 % compared to that of polypropylene. The analysis of the ecological impact of alternative utilisations of whey showed that PHA production is on par or even better when using the data from the pilot plant on the basis of € of revenue generated (as the products are used differently, this is a valid basis for comparison). The optimised PHA production process has only an ecological impact of 7 to 15 % per € generated compared to the conventional treatment of whey to produce whey powder. From this point of view, producing PHA has a clear ecological advantage.

This example shows how LCA can be used to explore and prioritise process optimisation if used consequently from the start of technological development.

In another recent study, Shahzad *et al.*[16] presented an LCA for a process generating PHA from animal residues, using the SPI methodology, too. This again is a study that assesses a process that starts from an industrial by-product, in this case slaughterhouse residues. The process is technically interesting, as it produces bio-diesel as a further product and utilises low grade bio-diesel and glycerol from bio-diesel conversion as carbon sources for the fermentation, but also covers part of the nitrogen demand by hydrolysed slaughterhouse residues. Excess biomass from the fermentation process may further be utilised to generate biogas.

This process is an example of a complex bio-refinery system that as one product generates PHA. The interesting point from an LCA point of view is that, here the ecological pressures of the process itself and the pre-chain of raw material generation and logistics are distributed to more than one product, thus reducing the load for a particular product. The result is that, PHA (as well as bio-diesel!) produced in this complex bio-refinery system clearly beats any fossil competitor: the footprint of PHA (using the EU27 electricity mix and natural gas as energy provision) is 62 % lower than that of low-density polyethylene (LD PE), and the life cycle Carbon Footprint of PHA is 54 % lower than that of LD PE.

The study also investigates the influence of different energy provision systems on the life cycle ecological impact of PHA production using this bio-refinery system, using in particular the electricity mix data for different countries. The analysis reveals that the ecological footprint of this process is strongly dependent on the energy provision system in these countries: PHA production using Norway's very clean electricity (more than 95 % comes from hydro-power) would reduce the footprint to 52 % of a process using the EU27 average mix, i.e. to only 20 % of the LD PE footprint. Using only renewable energy sources, the footprint can be reduced even further, to roughly 15 % of the conventional LD PE footprint.

The paper, however, also reveals the differences in the results when using different measures. This is particularly obvious when comparing the results obtained with the ecological footprint (calculated with the SPI method) and the Carbon Footprint for the electricity mix of France: whereas the Carbon Footprint for this electricity mix is 23 % lower compared to the EU27 electricity mix, the SPI-ecological footprint is 44 % higher, owing to the high ecological significance of nuclear energy in this method.

The examples discussed here clearly indicate the potential of LCA studies to guide technological development. LCA can help identify steps in the life cycle, as well as in production processes that are crucial to the environmental performance of a material or product. They can even help when comparing different sites and the choice of basic technological context, like the energy system used to operate a given process.

How to interpret LCA studies of PHA production and what to learn from them

The current body of literature about LCA of PHA production systems offers a wide variety of (often conflicting) perspectives (see Table 1). It might therefore be necessary to summarise the most important aspects to be considered when interpreting of LCA studies. Table 2 provides an overview on these aspects.

Although the results of LCA studies may be controversial, this method can be a powerful tool for engineers in developing and designing processes. This is particularly true for processes like PHA production that are part of complex life cycles, may use a wide variety of raw materials, and are strongly context-dependent because of considerable electricity consumption and unfavourable logistic parameters of raw materials, like waste and by-product flows from agriculture and industries. In these applications, it is advantageous to use highly aggregated measures, as they will provide clearer assessments of ecological pressures relative to each other. It is, however, necessary to check their normative basis carefully for congruence with the value system regarding ecological pressures that guides the development process in general. Table 3 lists the aspects that can be elucidated by LCA studies during process development and design, with a particular emphasis on those important in the case of PHA production processes.

Table 1 – *Summary of LCA study results*

Author	Ref./year	Main results	Note
Patel *et al.*	9/2005	Energy requirement and CO_2 life cycle emissions comparable to worse than fossil alternatives, less advantageous than other bio-polymers	Meta-study; covers early development stage of technologies
Pietrini *et al.*	13/2007	LC-CO_2 emissions strongly dependant on type of product	LCA of CRT monitors and car panels
Kim and Dale	12/2008	Lower CO_2 emission of PHB than fossil alternatives; illustrate impact of agricultural cultivation	
Khoo *et al.*	14/2010	Strong dependency of ecological impact on energy mix and place of production, no clear picture in comparison to fossil alternatives	LCA of plastic carrier bags used in Singapore; produced either locally or in US
Tabone *et al.*	11/2010	Better on GWP than fossil alternatives (especially PHA from corn stalks) but worse in other measures (ozone depletion, acidification,…)	Comparing 12 polymers, using a wide range of problem-oriented measures
Essel and Carus	10/2012	Better than fossil alternatives on CO_2 emissions and fossil resource depletion; comparable upper limits on both measures but considerably more potential than PLA on both measures.	Meta-study
Koller *et al.*	15/2013	Optimised industrial processes based on waste material have lower overall ecological footprint than fossil alternatives; high influence of electricity demand	SPI – LCA of PHA from whey
Shahzad *et al.*	16/2013	Strong impact of energy (in particular electricity) provision on ecological footprint of PHA; advantage if PHA is produced in a bio-refinery setting	SPI and Carbon Footprint – LCA of PHA from slaughter house waste

Table 2 – *Critical aspects for interpreting LCA studies*

Critical aspect	Why critical?
Normative base of valuation	Each evaluation has a (declared or hidden) normative base and thus vision of "ecologically desirable" processes. These visions are not congruent and sometimes conflicting. Comparison of assessments based on different measures is impossible.
Functional unit	Studies assessing end-use products (carrier bags, appliance housing, etc.) integrate the impact of manufacturing processes and material properties (weight, tensile strength, etc.) when comparing different alternative materials. Results may differ widely from comparisons of provision of unit amounts of material.
Development status of technology	PHA production processes are often still innovative, with large optimisation potential. This puts them to a systemic disadvantage to fully optimised processes generating competing fossil materials. LCA based on pilot plant/laboratory data are of limited significance for such comparisons.
Raw material	Raw materials for PHA production differ widely. The ecological impact of raw material provision is particularly strong for agricultural crops (corn grains, sugar beet, etc.), less so for by-products and waste flows.
Spatial context	Spatial context often defines energy provision patterns and logistical structures. These factors have considerable influence on the results of LCA studies.

Table 3 – *Aspects on which LCA studies provide insight*

Aspect	How can an LCA help?
Comparing different raw material options	LCA can provide a systemic picture on the ecological impact of different raw material options, summarising ecological pressures across the whole life cycle.
Identifying ecological hot spots	LCA studies can pinpoint those steps in the life cycle as well as in the process itself that contribute prominently to the overall ecological impact. These steps offer starting points for process optimisation.
Estimation optimisation potential	Assessing technological optimisations for ecological hot spots can help to estimate the reduction of ecological impact possible for full development of processes, and may allow appraisal of ecological competitiveness of products.
Supporting decision about location and size of plants	The energy system at a site as well as the logistical system supplying a plant depend on spatial context and have a prominent influence on the ecological performance of production processes. LCA studies support the decision about site and size of production plants.

Table 4 – *Critical parameters for ecological impacts of PHA production*

Critical parameter	How to reduce ecological impact?
Raw material	Crops like corn and sugar beet inflict large ecological impacts in their cultivation. PHA from by-products and waste flows has therefore an inherent ecological advantage.
Development status of technology	PHA production processes are usually still in early technological development stages. Exploiting all potentials in yield and energy efficiency can improve ecological performance considerably.
Energy provision	PHA processes consume considerable process energy and electricity. Particularly clean electricity provision will reduce the ecological impact of PHA production dramatically.
"Refinerise" production processes	Using more complex process schemes that generate a broader product portfolio and utilise raw materials fully will reduce the ecological impact allocated to any individual product.
Raw material logistics	For processes utilising wastes, agricultural and industrial by-products raw material logistics play a prominent role in ecological performance. Optimising plant size and resource logistics is important to reduce life cycle wide ecological impacts.

Some critical parameters influencing the ecological impact of PHA production can be deduced from the studies covered in this paper. Table 4 lists these parameters.

Conclusion

LCA studies for PHA production do not render a clear-cut picture of the ecological performance of these bio-polymers in general, and in particular with regards to their fossil competitors. Surveying these studies, however, reveals that PHA can indeed trump fossil competitors with regard to ecological performance, especially if they use industrial and ecological by-products and wastes, clean energy (in particular electricity), and exploit all possible optimisation potentials in the life cycle.

LCA studies are not unequivocal in their results when comparing technologies. Reasons for that include the different normative basis of evaluation methods, different contexts of the technologies compared, and different process limits used for the eco-inventories. They are, however, potent tools for supporting technological development and design, as they identify ecological hot spots and assess optimisation potentials.

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