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Innovative feedstocks in biodegradable bio-based plastics: a literature review

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Abstract

This paper reviews recent results of the literature on Environmental Life Cycle Assessment (ELCA) regarding the ecological impacts of alternative and innovative feedstocks for the production of bio-based and biodegradable polymers. The analysis was undertaken for the following popular polymers / polymer classes: polylactic acid (PLA) and the family of polyhydroxyalkanoates (PHA). The purpose of the analysis is to support decision-making regarding the feedstock assumptions underlying the life cycles of the products later explored in the project BIO-PLASTICS EUROPE. For each polymer, the pros and cons of different classes of feedstocks are weighed, and specific attention to existing trade-offs between different environmental categories as well as to issues in the comparability of studies paid. An overview on research results concerning the environmental performance of the currently still dominating first generation of bioplastic feedstocks is given. For second- and third-generation feedstocks, the results of recent studies are investigated in detail and compared (as far as possible) to outcomes for the first generation.

JEL codes

Q57, L65, Q21

Keywords

Bioplastics, Environmental Life Cycle Analysis, Polymer feedstocks, PHA, PLA

1 | Introduction

By now, a large amount of different bio-based plastic polymers has been developed and entered the markets, being adapted to a wide array of applications. Nevertheless, market shares of these polymers are in most areas still negligible. High production costs impair price competitiveness in relation to their fossil-based counterparts. In the future, learning effects and the exploitation of scale opportunities could remedy this fact, provided that capacities substantially increase. For this, in turn, consumer acceptance will be the key. To compensate current disadvantages in pricing, it is essential to convince consumers that bio-based materials are superior with respect to sustainability considerations. This requires detailed environmental analyses not only of the refinery processes, but of the whole value chains.

Under the prevailing technologies, feedstock cultivation is one of the critical factors, due to its various and potentially significant ecological impacts. Against this background, a considerable number of innovative feedstocks have been proposed and tested in recent years. Based on their development status, these feedstocks are usually classified as belonging to one of three generations. The first generation consists of substances retrieved from plants that are otherwise used in the food sector, involving the critical aspects discussed above. The second generation can be defined as lignocellulosic feedstocks gained from non-food crops or as by-products from the cultivation of food crops, while the third generation consists of the currently most innovative forms of feedstock extractions from a range of substrates like whey, industrial and municipal waste or algae. All these feedstocks require specific forms of treatment and thus imply highly heterogeneous production chains. As a consequence, one cannot instantly classify them as more or less sustainable than the currently dominating first generation. Instead, an evaluation of their environmental performances requires careful analysis, ideally with a transparent and widely accepted method like Environmental Life Cycle Analysis (ELCA).

This report provides an overview on current research results from the ELCA literature on the environmental performances of second- and third-generation feedstocks for producing bioplastic polymers/polymer families polylactic acid (PLA) and polyhydroxyalkanoates (PHA) in comparison to existing benchmarks. Preparing such an overview requires to cope with partially serious limitations of the comparability of different studies. First, this concerns discrepancies in the reference materials chosen in the analyses. Not all studies investigating the impact of choosing alternative feedstocks consider the case of producing the same polymer by standard process routes (i.e. with first-generation feedstocks) as reference, which would strictly be required for functional equivalence. Second, system boundaries differ to some degree between studies. This specifically concerns the consideration of by-products and alternative usage options for input resources.

Third, authors apply different assessment methodologies and select distinct impact categories for their reporting. Acknowledging these limitations, this overview does not attempt to make quantitative comparisons between research results, but rather tries to ascertain qualitative patterns in the studies investigated.

The paper is structured as follows: Section 2 introduces the three different generations of bioplastic feedstocks as they are commonly distinguished. Section 3 summarizes literature findings on first-generation feedstocks, motivating the search for more sustainable ways to extract the necessary organic raw material. Section 4 is then devoted to a detailed analysis of existing ELCA studies on the use of second- and third-generation feedstocks in the production of the two polymer categories investigated. In both cases, after a brief description of the polymer, an overview on the current feedstock discussion is given. Then, specific studies are summarized by reflecting with methods and results, and general implications are derived. The paper closes with a tentative summary of the pros and cons of different feedstock categories.

2 | Three generations of feedstocks

Bioplastics feedstocks are generally divided into first-, second- and third-generation feedstocks according to their development stage. While it is relatively straightforward which feedstocks can be assigned to the first generation, there is no generally accepted definition of the second and third generation in the literature.

First-generation feedstocks are usually carbohydrate-rich plants that are also suitable as food or animal feed. Today, most bioplastics products are based on first-generation feedstocks such as corn and sugar cane. These feedstocks have a high degree of technical maturity. However, the cultivation of first-generation feedstocks is a critical factor due to intensive agriculture and the resulting negative influences on humans and nature (see section 3). For this reason, alternative feedstocks, that do not require the dedicated use of agricultural land, have been developed and tested.

The second generation includes feedstocks that are not suitable for food or animal feed. These can be either non-food crops (e.g. cellulose) or by-products from first-generation feedstocks such as corn stover or sugarcane bagasse. The use of second-generation feedstocks has not yet reached a high degree of commercialization. This is due to the relatively high costs associated with the conversion of these feedstocks (Ögmundarson et al. 2020).

The third generation includes the currently most innovative feedstocks, which are still at an early stage of development. It comprises biomass from algae or industrial or municipal waste. Since the production of bioplastics varies greatly depending on the chosen feedstock, it is not immediately clear whether the feedstocks of the second or third generation are more environmentally friendly than the ones of the first generation. For this reason, the individual process steps, including all inflows and outflows, must be evaluated using a comprehensive ELCA.

Figure 1: Overview on feedstock generations

First Generation	Second Generation	Third Generation
• Corn • Wheat • Rice • Sugar cane • Sugar beet • Potato	• Wood • Wheat straw • Sugar cane bagasse • Corn stover • Palm fruit bunches • Switch grass	• Biomass from algae • Municipal waste • Industrial waste • By-products from food industry

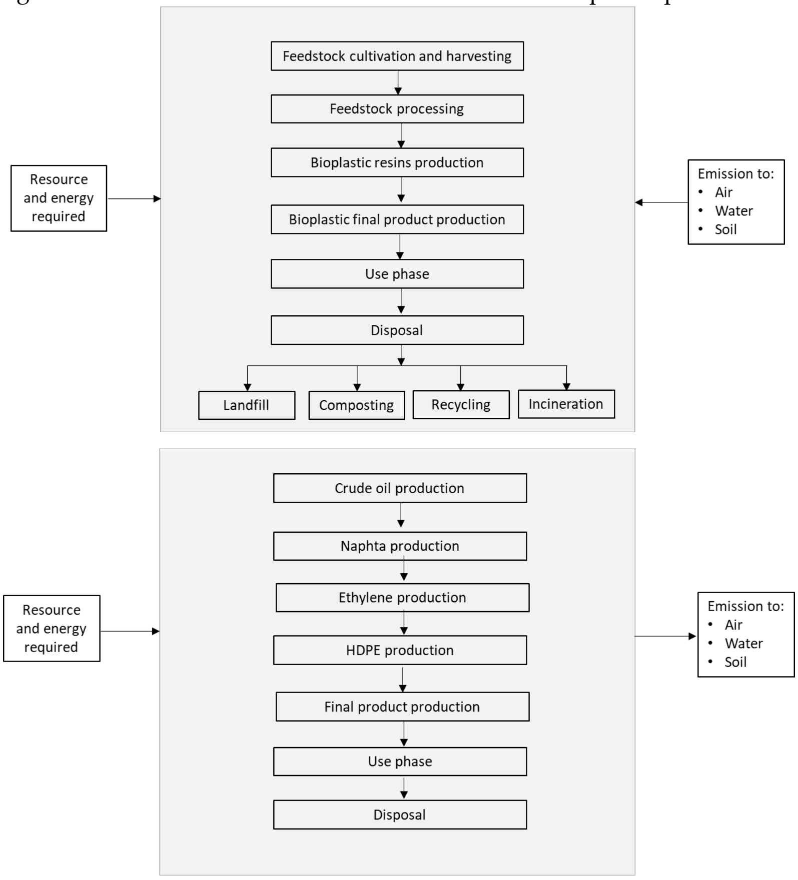
Source: own representation

3 | Environmental assessment of first-generation feedstocks

Currently, the majority of bio-based plastics are made from first-generation feedstocks, most of which are carbohydrates derived from agricultural crop production. For large-scale production, starch from corn grains and sucrose from sugar cane are used in particular (European Bioplastics 2019, Ögmundarson et al. 2020). While mass production leads to cost advantages, the use of first-generation feedstocks can also have disadvantages, especially for humans and the environment.

To identify and quantify these negative influences, scientists often use a life cycle assessment (LCA). This method enables to identify various environmental impacts associated with the different steps in the product's life cycle. An LCA also allows to determine which impacts are directly related to the choice of feedstock. The life cycle (cradle to grave) of a first-generation feedstock based plastic begins with the cultivation and harvesting of the crop and ends with an end-of-life (EoL) option, which can range from landfill to recycling (see Figure 2). To find out how the choice of feedstock influences the results of the LCA, the first steps in the life cycle - cultivation, harvesting and processing of the crop - must be particularly focused in the analysis. All resources required to produce the biomass, as well as the emissions to water, soil and air, must be recorded and summarized in impact categories in order to make them comparable. In general, to assess the environmental impacts associated with the cultivation of the feedstock and the biomass production, LCA studies often use the following impact categories: fossil deposition, ecotoxicity, acidification, eutrophication, climate change, land use and water use.

Figure 2: Process schemes for bio-based vs. fossil-based plastic production



Source: own representation based on Rattana et al. 2019

Most of the LCA studies that analyse first-generation feedstocks perform a comparative LCA and compare the environmental impacts of bio-based plastic to fossil-based plastics. These studies predominantly state that bio-based plastics of the first generation are even inferior to their fossil counterparts due to intensive agriculture and the associated environmental influences. The use of pesticides and fertilizers during the cultivation of the feedstock is often identified as the main cause of damage to human health and the environment.

In most studies, the eutrophication and acidification effects of bio-based products are higher than those of fossil-based plastic products. This is due to the fact that the nutrients from the fertilizer applied during the cultivation of the crops can enter water bodies and lead to eutrophication (Changwichan et al. 2018). The emissions into the soil from the applications of fertilizer during cultivation also increase the acidification effect of bio-based plastics (see e.g. Rattana et al. 2019, Gironi & Piemonte 2011). The production and the usage of nitrogen fertilizers in the harvesting and cultivation also contribute to the global warming impact. Some studies take the CO_2 uptake from the atmosphere during the plant growth into account (see e.g. Vink & Davies, 2015; Changwichan et al. 2018) and consider the net CO_2 effect. Changwichan et al. (2018), for example, find a negative global warming effect associated with cultivation, because the CO_2 absorption of plants is greater than the emissions released during the production and use of fertilizer. However, Rattana et al. (2019) point out that it is important to also consider the CO_2 release at the end of the bioplastic product's life cycle that compensates for this effect. For this reason, Rattana et al. (2019) and Groot & Boren (2010) do not include CO_2 uptake during cultivation and find that the CO_2 emissions for the bioplastic product were greater than those for fossil-based plastics. The production of the bioplastic polymer contributes the most to global warming, but the cultivation phase makes the second largest contribution (Rattana et al. 2019).

Another disadvantage of the intensive agriculture, which is necessary when using first-generation feedstocks for bioplastics production, is the high demand of water when cultivating the raw materials. Therefore, the water consumption is higher than for fossil-based products. Since arable land is needed for the cultivation of the raw materials, the land consumption for bio-based plastics was classified as significantly higher than for fossil-based plastics (Changwichan et al. 2018). The impacts associated with land use change, i.e. the intended transition from the original use of land (e.g. forest or grass) to the cultivation of biomass (Vink & Davies 2015), must also be considered. A great advantage of bio-based polymers is the use of renewable raw materials instead of fossil resources. Biobased plastics therefore naturally consume fewer fossil resources than conventional plastics (see e.g. Groot & Boren 2010, Rattana et al. 2019). Most of the energy consumption takes place during polymer production, while the cultivation of the raw materials requires relatively little energy. If renewable energies are used in bio-based plastics production, this would save even more fossil resources (Rattana et al. 2019). The advantage of using renewable resources can be further enhanced by a recycling process, as this would lead to savings in the use of fertilizers and pesticides, which have a strong impact on human health and the quality of the ecosystem.

Overall, LCA studies have shown that the main advantage of bio-based polymers, the use of renewable resources instead of fossil resources, is outweighed by the damage to human health and the quality of the ecosystem associated with the cultivation of feedstock (Gironi & Piemonte 2011). The majority of LCA studies conclude that bioplastics based on first-generation feedstocks are not always more environmentally friendly than fossil alternatives, especially due to intensive agriculture and the use of pesticides, fertilizers, land and water. Another critical point is that first-generation feedstocks such as corn and sugar are also used as food and therefore bioplastics production is in competition with food production. There is concern that an increase in demand for corn and sugar due to excessive bioplastics production could lead to higher food prices.

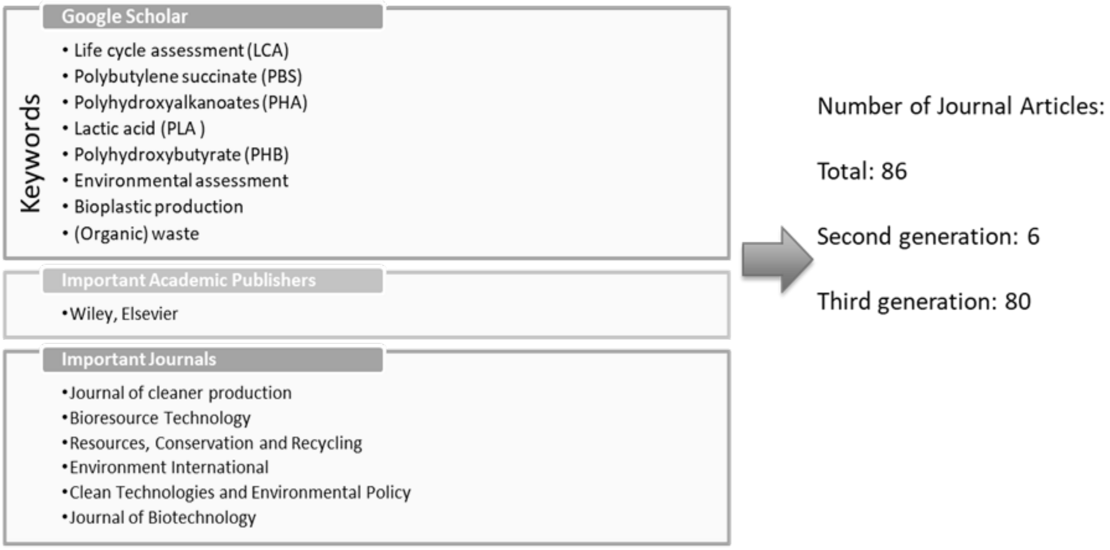
4 | LCA – Literature on second and third generation feedstocks

4.1 | Procedure of literature search and evaluation

In order to find the most important journal articles analysing the life cycle of different bioplastic polymers based on different feedstocks, an extensive literature search was conducted. The literature search was mainly carried out with Google Scholar by searching a range of keywords. In addition, the websites of important publishers such as Wiley and Elsevier were searched for journals with matching topics. These journals were then also searched using the keywords. In a final step, the references of the articles found were inspected to see whether further studies were cited there. The journal in which most of the articles were found is the Journal of Cleaner Production. A total of 86 suitable articles were found. Of these, 6 studies examine second-generation feedstocks, and 80 studies examine third-generation feedstocks. Table 1 gives an overview of the procedure, the used keywords, and the most important journals.

Of the 86 articles found in total, 21 articles were studies that evaluated the environmental implications of second- and third-generation feedstocks for the production of the relevant polymers based on the ELCA methodology. In what follows, studies focused on the polymers PLA and PHAs are scrutinized in detail. For a better overview, the papers are roughly grouped by feedstock category. Moreover, discussions for each polymer (group) culminate in a cross-feedstock general implication section. Given the heterogeneity of assumptions and assessment methods among the papers, this cannot take the form of a direct quantitative comparison of assessment results. Instead, to have at least a semi-quantitative perspective, we follow the approach proposed by Vendries et al. (2020) and broadly categorize the results of studies by impact category according to the impact measured for the innovative feedstock investigated in relation to the impact measured for the corresponding first-generation reference feedstock (usually corn grain). In this way, the problem of differing assumptions can be circumvented, as long as the studies are internally consistent. Table 2 presents our categorization approach, the resulting grouping is presented in the corresponding summary sections.

Table 1: Literature review procedure



Source: own representation

Table 2: Categorization of impact assessment results in studies

Category	Impact values innovative feedstock / reference feedstock	Interpretation
-2	< -0.25	Innovative feedstock shows considerably lower impacts than reference
-1	> -0.25 & <0	Innovative feedstock shows slightly lower impacts than reference
0	0	No measurable difference in impacts
1	> 0 & < 0.25	Innovative feedstock shows slightly higher impacts than reference
2	> 0.25	Innovative feedstock shows considerably higher impacts than reference

Source: own representation

4.2 | Feedstocks for PLA production

4.2.1 | General description

PLA is a bio-based and biodegradable polymer built from lactic acid molecules. It is a thermoplastic polyester, which becomes softer when heated and hard when cooled. It can be cooled and heated several times without altering its mechanical and chemical properties. This allows them to be formed and processed via liquification and moulding techniques, as well as to subsequently recycle the material via the same processes. Due to this flexibility and other technical properties, PLA is technically suitable for a wide range of applications from single-use packaging to durable consumer goods. As feedstocks, glucose and sucrose are in use. In case of glucose, corn grains are still the dominating biological source. After harvesting, the maize starch is extracted from the grains. Then, starch molecules are decomposed into glucose molecules by means of a hydrolysis procedure. Glucose is dried and then enters an industrial fermentation process employing bacteria. The resulting lactic acid solutions are converted to lactide, purified via crystallization, and finally polymerized to PLA. In case of sugar cane, the general procedure is similar, with the exception that sucrose extracted from sugar cane stalks represents the input for the fermentation procedures (Farah et al., 2016; Lunt, 1998).

From an economic perspective, PLA production is currently more cost efficient than production of other bioplastic polymers, due to the fact that technical knowledge and production capacities have reached a comparatively high level. In terms of market shares, PLA exhibited according to estimates from European Bioplastics in 2019 with 13.9 % the second largest share in global production capacities of all bioplastic polymers (European Bioplastic, 2019). Over the next five years, this share is expected by European Bioplastics to remain roundabout stable. Concerning final products, rigid packaging, flexible packaging and textiles are the dominant application areas.

4.2.2 | Overview on feedstock discussion

By now, a variety of resources for the production of lactic acid have been under discussion. Main purpose of these development processes has been to overcome the environmental issues associated with land use and competition with food production that are connected with the current feedstock generation of food crops. Among these, the use of residual plant material from the cultivation (stover) and processing (e.g. sugar cane bagasse) of these crops as cellulose-based feedstocks has already been discussed for quite a while. The fact that these materials are obtained as a by-product prevents or at least mitigates the caveats against the first-generation feedstocks. Moreover, several suggestions have been made in recent year to decouple PLA production from agricultural land use completely. One strand of this literature focuses on the utilization of by-products and waste from the food industry which are of otherwise no or low economic value. Harbec (2010) and Broeren et al. (2017) analyse the use of wastewater accruing in the industrial processing of potatoes. Liu et al. (2018) investigate the production of lactic acid from cheese whey, with lactose and proteins as feedstocks. Juodeikiene et al. (2016) are assessing ways to improve the yield from cheese whey, by comparing different bacteria species and enzymes used in fermentation. Nguyen et al. (2013) examine a scenario where waste from the industrial extraction of curcuminoid used in medical applications from the *curcuma longa* root is fermented to lactic acid through simultaneous saccharification and fermentation. De la Torre et al. (2018) consider a mixture of orange peel waste and corn steep liquor as substrates. Pleissner et al. (2016) investigates waste from coffee production, coffee pulp, as substrate. Alves de Oliviera et al. (2020) propose the use of sugar beet pulp obtained as a side product for animal feed from the process of extracting sugar from sugar beets.

Another strand examines the potential to shift from land-based to sea-based resources. The cultivation and fermentation of sea plants rich in carbohydrates is seen as an opportunity to construct new production routes from scratch and thus preserve existing food production chains from being disrupted by plastic manufacturing. In this vein, Helmes et al. (2018) explore the use of the seaweed *Ulva spp*. in lactic acid production. Ögmundarson et al. (2020) experiment with the cultivation of brown algae of the species *Laminaria sp.* as feedstock source.

In the following section, approaches that present evidence on ecological impacts in the form of environmental LCAs will be discussed in detail. Characteristics of the corresponding studies are summarized in Figure A 1 in the Appendix.

4.2.3 | Examination of ELCAs

<u>**Cellulosic feedstocks**</u>

Adom & Dunn (2016) compare the emission flows from polymer-grade lactic acid production based on corn-stover-derived cellulosic sugars with those based on corn-derived glucose. Moreover, both cases were compared to the production of ethylene as fossil-based benchmarks. In its scope, the analysis is limited to GHG emissions and fossil energy consumption as environmental categories. Moreover, GHG emissions from potential land-use change associated with feedstock production are not considered. When focusing exclusively on the cradle-to-gate part of the life cycle (i.e. ignoring issues of EoL-treatment), the authors estimate clearly lower values in terms of both GHG emissions and fossil energy consumption for cellulose-based production in comparison to the first generation technology. The differences are almost completely attributable to discrepancies in the sugar production (i.e. the first stages of the chain), only to a minor degree to the subsequent fermentation stage. When integrating EoL-treatment into their analysis, the authors further distinguish between two scenarios. In the first scenario, no re-release of the carbon embodied in the lactic acid is assumed within the time horizon of the analysis, justifying the deduction of a carbon credit from the GHG emissions attributed to the carbon uptake. This is a case associated with the use of lactic acid in products of long-term use. In the second scenario, a complete degradation of the bioproduct in a landfill is assumed, associated with a complete re-release of the carbon into the atmosphere. In both scenarios, net GHG emissions along the whole cradle-to-grave cycle are found to be lower for lactic acid (both feedstock types) than for ethylene. In the landfilling scenario, the difference is more striking, because of the substantially higher release of CO_2 by ethylene in the landfill stage. Moreover, as the feedstock question is not expected to make a difference for emissions in EoL-treatment, the general advantage is more pronounced for the second-generation variant of a cellulosic feedstock.

Daful et al. (2016) analyse lignocellulose gained from sugarcane bagasse and leaves as an alternative second-generation feedstock. Bagasse is the term for the pulpy substance that remains as a residue after the juice has been extracted from the sugarcane. The environmental implications of integrating these by-products of sugarcane cultivation into the existing process of sugar production in South Africa and a subsequent production of lactic acid are assessed. In comparison to fossil-based lactic acid as a benchmark, the study finds not only emissions savings in terms of GHG emissions, but also with respect to substances causing eutrophication and dangers to human health. However, a comparison to PLA from first-generation feedstocks, e.g. the sucrose directly gained from the sugarcane plant, is missing. Hence, the benefits of the possibility to use multiple plant parts (and thereby reduce land intensity) are not quantified. Opportunity costs of giving up alternative uses of bagasse (e.g. input in pulp production) and leaves (e.g. energy source) are not addressed as well. Hence, the existence of a net advantage compared to first-generation feedstocks remains an open question.

Ögmundarson et al. (2020) also consider corn stover as a second-generation feedstock and compare it to corn-based glucose as a first-generation alternative, but not to a fossil-based benchmark. This study does not limit its attention to greenhouse gases and energy use, but also incorporates more locally oriented impact categories associated with ecosystem quality and human health. Moreover, emissions from indirect land use change applicable to the first-generation feedstock are considered. At the same time, by applying system expansion, they also account for a potential downside of corn stover: the fact that stover when utilized as a feedstock can no longer be used as a biological fertilizer and thus requires the additional production of fertilizers as a replacement. In contrast to Adam & Dunn (2016), they estimate a higher GHG impact for lactic acid from corn stover than from corn-based glucose, despite the incorporation of land use effects. The authors explain this by the mentioned system expansion, i.e. the emissions resulting from the required additional production of synthetic fertilizers in case of corn stover. Probably for the same reason, the first-generation feedstocks also perform better with regard to natural resource use as well as categories associated with human toxicity and ecotoxicity. However, the authors do not ascertain to what extent this result is driven by specific assumptions regarding the nature of the substituting fertilizer. By contrast, as expected, corn stover outperforms corn-based glucose in terms of land use and water consumption, i.e. impact categories mainly associated with the agricultural process. A sensitivity analysis reveals that ignoring indirect land use change would narrow the overall advantage of corn-based glucose considerably.

Liquid organic waste

Harbec (2010) investigates the impacts of producing PLA from starch obtained from wastewater accruing in the industrial processing of potatoes to chips or French fries. As this residue represents an unavoidable by-product of potato processing, no issues associated with food competition arise. By applying a centrifuge process, the starch concentration of the wastewater is increased before undergoing fermentation. A cradle-to-gate ELCA of the production steps up to the generation of lactic acid is performed and compared to lactic acid generated from corn-based glucose as a reference case. In the allocation procedure, the emissions associated with potato processing were not considered, which was justified by the absence of an economic value of the potato waste. Emissions reported for the potato waste process are largely based on own experimental data. In all four endpoint categories considered in impact assessment (resource depletion, climate change, ecosystem quality, human health), substantially higher impacts were estimated for the potato waste scenario, with the biggest discrepancies to be noted for resource depletion and climate change. The explanation for this result lies mostly in the high energy intensity of lactic acid production from potato waste, especially in the comparatively high steam consumption during the pre-heating and purification stages: since the lactic acid obtained from fermenting the waste starch is more diluted, more water needs to be vaporized in comparison to the reference technology. The resulting higher fuel use causes stronger contributions to resource depletion as well as GHG emissions. The underlying reasons for this inefficiency are both the insufficient starch content of the wastewater and the low maturity level of the conversion technology. Hence, substantial yield improvements will have to be achieved (and demonstrated) to improve the ecological balance.

Broeren et al. (2017) analyse within a large-scale comparative cradle-to-gate ELCA study of different types of starch-based plastics a similar scenario of PLA production based on starch from potato waste. Again, the use of wastewater from potato processing is utilized. The data for this variant stem from modelling assumptions instead of own experiments. In contrast to Harbec (2010), they identify a slight improvement in the environmental performance concerning GHG emissions and fossil resource depletion in comparison to the first-generation alternative, and a more substantial one for the agriculture-related categories land use and eutrophication. However, apart from the different assessment method, comparability is limited for several reasons. First and foremost, the first-generation benchmark differs: Broeren et al. (2017) examine virgin starch from potato cultivation instead of corn-based glucose. Given that production from corn is currently the dominant technology for PLA (see section 2), this puts the relevance of the benchmarking into question. Second, they disregard the emissions related to the centrifugation process of the starch wastewater. On the other hand, emissions associated with direct or indirect land use change are disregarded as well, a fact suggesting an underestimation of the benefits from the wastewater solution.

Sea plants

Helmes et al. (2018) undertake an exploratory ELCA for the use of the seaweed *Ulva spp*. as a feedstock in lactic acid production. The use of this species was justified by its comparatively high sugar content. The seaweed was hydrolyzed to obtain glucose and afterwards entered a fermentation process. A scenario based on own experimental data was compared with an optimization scenario including improvements in seaweed cultivation and lactic acid purification as well as lactic acid from corn-based glucose as benchmark. By applying system expansion, the beneficial environmental effects stemming from the utilization of by-products of the process chain (the seaweed residues after hydrolyzation and gypsum obtained in the purification) were explicitly integrated into the analysis. In the impact assessment, they consider a broad range of endpoint categories, which are aggregated to a (weighted) ReCiPe score. For the experiment-based seaweed scenario, this score turns out to be more than ten times higher than the reference maize scenario. This is mostly due to significantly larger impacts in the categories human health, fossil depletion and particulate matter formation. The authors identify differences in electricity consumption as the major underlying source for this bad performance of seaweed production. According to their data, almost 99 % of electricity consumption occurs in the seaweed cultivation stage, in connection with water pumping and aeration of the seaweed basins. At the same time, results of the optimization scenario raise hopes that gains in material efficiency within cultivation and purification can sizeably improve the environmental outcomes. The authors expect efficiency gains associated with future upscaling as another source of substantial improvement, which however cannot yet be quantified.

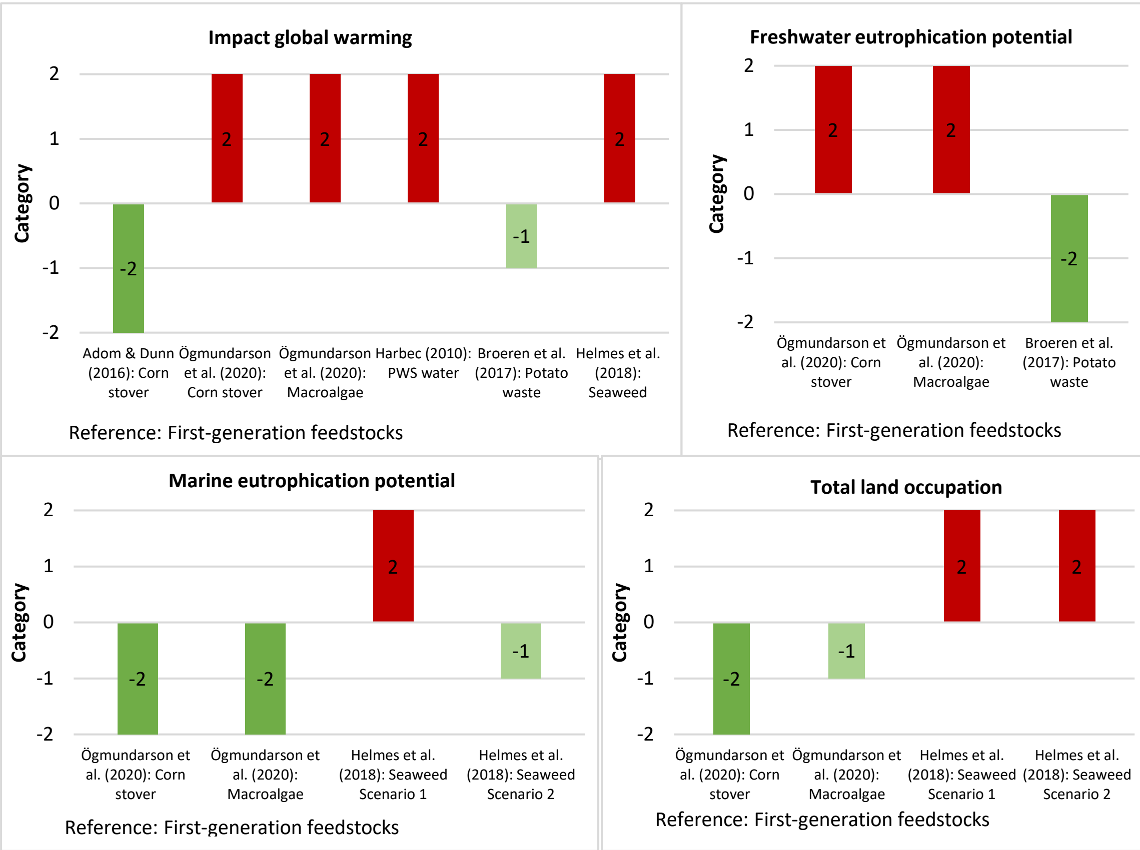
Ögmundarson et al. (2020) analyse in their study the environmental benefits of macroalgae as an innovative feedstock in lactic acid production (in addition to corn stover as discussed above). They investigate species from the brown algae genus *Laminaria sp.*, mainly because of a high content of carbohydrates, and compare outcomes with first-generation maize feedstocks and corn stover. The calculations were undertaken based on pre-existing databases. In their assessment of endpoint categories, the macroalgae perform worse than the two alternatives in all three categories (human health, ecosystem quality and natural resources). The biggest discrepancies are visible for fossil resource depletion and contribution to global warming. The high energy intensity of the biorefinery processing of microalgae is mainly responsible for this. The analysis reveals that the drying process necessary after chemical pre-treatment and before fermentation of the biomass is a main driver. An improvement could be achieved by enhancing the biomass content of the algae that can be used in fermentation. A sensitivity analysis shows that the possibility to ferment the substance alginate as well could reduce overall contributions to the single impact categories by more than 20 %, due to reductions of the necessary biomass input per kg of lactic acid. Future improvements in production technologies thus promise a considerable potential also from an environmental perspective. Moreover, the authors demonstrate the dependence on the assumptions regarding the energy mix: assuming the current energy mix of China instead of the US would considerably worsen the overall environmental balance and at the same time increase the gaps between the three feedstock scenarios. This hints at the importance of specifying the production location in the LCA.

4.2.4 | Implications

In case of PLA, the extent of innovative feedstocks for which comprehensive studies on the environmental performance are available is still limited. Figure 3 presents a comparison of literature results for those impact categories for which at least three studies were available. Among the existing evidence, the second-generation feedstock (ligno)cellulose obtained as by-product from plant cultivation has gained specific attention. Its basic advantages are evident: when being harvested exclusively as a by-product within existing process routes for corn, sugar or cereal production, no environmental issues related to land transformation arise. Moreover, as fertilizer input, water consumption and machinery use are thus effectively shared between the agricultural outputs, the emission reduction also applies to the cultivation process of the feedstock as a whole following the allocation principle. In this way, not only impacts in global environmental categories related to climate change could be reduced, but also in categories associated with local damages to soil, water and human health. However, as demonstrated by Ögmundarson et al. (2020), an environmental analysis should consider that even though these agricultural by-products are often not put to notable economic use, they are not worthless from an ecological point of view. Plant material remaining on the field after harvesting provides ecological services such as erosion protection and an increase in the carbon content of the soil, or could alternatively be incinerated to replace fossil fuels as an energy source. LCAs investigating the benefits of cellulose feedstocks should take the opportunity costs of these alternative uses into account, ideally by means of system expansion. The analysis by Ögmundarson et al. (2020) shows that such a consideration can worsen the total environmental performance quite substantially.

In comparison, organic waste obtained from industrial processing appears superior: alternative use options are very limited. Even more so, their use as bioplastic feedstock avoids a potential emission-intensive final disposal on landfills or in nature. By incorporating the carbon contained in these particles into plastic polymers, its emission as CO_2 back into the atmosphere is at least delayed for a potentially significant amount of time. Nevertheless, this category of feedstocks also has its idiosyncratic environmental risks, which are primarily related to the low maturity level of the processing technology. It is especially the currently high energy intensity of the bio-refinery process that worsens the environment balance considerably. The same consideration applies to another innovative feedstock category for PLA in the literature, the use of algae and related sea plants. Here as well, the complexity of the processing and its significant energy requirements represent an ecological burden. In the future, efficiency increases through scale effects and process innovation, but also higher shares of renewables in the energy mix of producer countries could remedy this fact. It remains to be seen to what extent this will materialize in actual emission reductions in the medium term.

Figure 3: ELCA literature results by impact category for PLA feedstocks



Source: own description; relative performance compared to reference feedstock (see 4.1)

4.3 | Feedstocks for PHA production

4.3.1 | General description

PHA do not represent a single polymer, but a whole family of polyesters. Unlike other bioplastic materials, they are not exclusively generated artificially, but are also produced in nature. They are bio-based and biodegradable polymers, which exhibit the properties of thermoplasticity and UV-stability. Due to their heterogeneity, the family of PHAs is potentially suitable for a wide range of applications from packaging to medical items. Polyhydroxybutyrate (PHB) is currently the most widely discussed polymer within the family. Its mechanical and physical properties are similar to those of the fossil-based polypropylene (PP), thus representing a potential substitute in applications like food packaging and agricultural foils. As feedstocks, the same range of biomaterials as in case of PLA are currently in use. The first steps of production are thus equivalent: extracting carbohydrates from cultivated food plants and (in case of starch) breaking polymers down into glucose monomers through hydrolysis. Concerning the subsequent production steps, several kinds of process routes have been proposed and applied, which can be grouped into the classes of microbiological, enzymatic and chemical processes (Alcântara et al., 2020). This puts a greater emphasis on the fermentation stage, also (as it turns out) concerning the environmental aspects of the process.

Even though many researchers consider the PHA family as particularly promising materials and despite the fact that its technical potentials are already under discussion for quite a long period of time, its overall market share is still very modest. European Bioplastics records for the year 2019 a market share of merely 1.2 % on the total bioplastic segment. For the future, they expect this to increase. For 2024, a share of 6.6 % is projected, which is however still considerably lower than what is expected for PLA or polybutylene adipate terephthalate (PBAT) (European Bioplastics, 2019). There is an agreement in the literature that the reasons for this are primarily to be found on the economic side. Mainly due to the energy- and material-intensive fermentation and extraction steps, production costs are comparatively high, both in comparison to PLA and to competing fossil-based plastic polymers (Madkour et al., 2013). Mass production with its scale advantages and standardization effects could remedy this fact but would require a significant demand impulse.

4.3.2 | Overview on feedstock discussion

For the PHA family, the literature on feedstock solutions is particularly large and diverse. Most of the research done focuses on PHB as a concrete example. Moreover, a considerable range of papers is devoted to third-generation feedstocks. Among these, substrates related to waste generation have generated particular attention in recent years. On the one hand, this concerns solid waste or wastewater obtained as a residual from production processes in the food industry. For instance, Shahzad et al. (2013) consider the use of slaughterhouse waste as a source for fatty acids as PHA feedstock. Similarly, Bhatia et al. (2018) examine coffee waste as substrate, whose oil is extracted and the contained fatty acids used as feedstock. Zarroli (2020) investigates the usability of starch obtained from wastewater occurring in potato processing. Another literature spectrum investigates the suitability of municipal waste. Morgan-Sagastume et al. (2016) examine the opportunities of integrating PHA production into a municipal wastewater treatment plant. Sangkharak et al. (2020) investigate the potential to use waste cooking oil as a substrate for PHA production, making use of contained free fatty acids as a feedstock. Kendall (2012) considers the use of organic waste generated as a residue in material recovery facilities.

Another strand of literature deals with the feedstock potentials of several forms of by-products in the bioeconomy sector. Koller at al. (2013) experiment with cheese whey as a by-product in milk processing. Thinagaran & Sudesh (2019) test the use of sludge palm oil obtained as a by-product in palm oil milling. Abdel-Rahman et al. (2017) investigate the use of glycerol as a by-product in biodiesel production. Penkhrue et al. (2020) test the use of pineapple peel solution as a substrate. Heng et al. (2017) investigate rice husks as a substrate, making use of its cellulose content as a feedstock. Ye et al. (2018) operate with corn steep liquor as a substrate, a by-product of the wet milling process of corn. Pernicova et al. (2018) demonstrate the possibility to obtain PHA from the controlled degradation of chicken feather waste. Finally, the use of biogas has been subject to investigation, which in case the gas stems from landfill emissions offers the opportunity of a closed carbon cycle. Rostkowski et al. (2012) analyse the environmental impacts of such a cycle. The firm Mango Materials has already put such a cycle into practice (Pieja et al., 2016).

In the following section, approaches that present evidence on ecological impacts in the form of environmental LCAs will be discussed in detail. Characteristics of the corresponding studies are summarized in Figure A 2 in the Appendix.

4.3.3 | Examination of ELCAs

Cellulosic feedstocks

Kurdikar et al. (2001) analyse the life cycle impacts of PHA production based on corn stover from genetically modified corn. Regarding the production technology, four different scenarios were investigated, which merely differ in the energy mix assumed for the refinery process. Precisely, they compare a scenario where corn stover residues after biopolymer extraction are used as energy source for the later production stages with scenarios where these stages are fuelled solely by different mixes of conventional (fossil-based) energy carriers. The analysis solely focused on global warming impacts, thus presents only a limited picture of the environmental implications. Another limitation is that no comparison to corn grain as an alternative feedstock was made. Instead, production of a fossil-based polymer was chosen as a benchmark. Contrary to later studies, they conclude that corn-stover-based PHA has a stronger impact on global warming than the fossil benchmark for the scenarios with a conventional energy mix. This changes when the stover residual is recovered and used as an energy source through incineration, which allows for both a reduction of internal use of fossil sources and the generation of a small amount of surplus electricity, whose feed-in into the electricity grid justifies an additional carbon credit. Given the age of the study, the former results could be explained by a still low degree of technical maturity / high level energy intensity at the time of study and is thus unlikely to be representative for current production technologies.

Kim and Dale (2005) examine a different kind of scenario. They deal with an integrated system, in which PHA is derived from an integrated processing of both corn grains and stover. Regarding the question of energy use, they adopt the scenario of Kurdikar et al. (2001) that assumes the recovery of corn stover residues from the refinery processes as energy sources for the generation of electricity and steam. On the downside, they take into account that the removal of the stover from the field reduces the accumulation of carbon in the soil. This system is compared to PHA produced purely from corn grain. They consider not only global warming impacts, but also the local damage categories acidification, eutrophication, and photochemical smog. With respect to the fermentation technology, they distinguish different scenarios, which differ in technical assumptions regarding the allocation procedure. Concerning global warming, they measure a negative total impact for this integrated system throughout all fermentation scenarios. Hence, the integrated system offers a global warming credit. By contrast, for the reference production system purely based on corn grain, the global warming impact is clearly in the positive range. The main reasons for this difference are the higher agricultural productivity of the integrated system (due to using several parts of a plant) and the carbon credits associated with the excess energy generated from burning the stover residues. Regarding the other impact categories, the integrated system performs better as well, as a side effect of the lower external energy requirements of the process.

Zhong et al. (2009) compare the environmental consequences of corn-stover-based PHA both with PHA from corn grain and PHA from cheese whey, i.e. a third-generation feedstock (see also next chapter). The input data for the corn stover scenario is completely adopted from Kurdikar et al. (2001). Unlike the previous studies, they do not consider the option of using stover residuals as energy source. The impact assessment is structured based on ecosystem damage and human health damage as aggregate endpoint categories. In both categories, substantially higher damages are reported for corn stover than for the two other feedstocks. In particular, it is the respiratory damage that makes a difference. This is attributable to a high level of steam consumption in the corn stover scenario, exceeding the one estimated for cheese whey by more than four times. Of course, the high energy intensity of the process can also be partially attributed to the lower degree of technical maturity, at least in comparison to corn grain. However, the result also rests on the assumption of the sole use of non-renewable energy carriers. Again, these results demonstrate the necessity of exploiting the energy potential of residual particles to improve the environmental balance.

<u>**Liquid organic waste**</u>

Koller et al. (2013) investigate the ecological effects of PHA produced from whey in comparison to fossil-based polymers polyethylene terephthalate (PET), polyethylene (PE), PP and polystyrene (PS). They do not apply standard impact assessment categories, but a unidimensional ecological footprint index previously developed by some of the authors, calculating the area that is needed to integrate a production process sustainably into the existing ecosphere. Technically, they consider a scenario where whey is collected from dairies, concentrated to achieve a higher lactose content, ultrafiltrated and hydrolyzed to split lactose into its glucose and galactose molecules, which then enter the fermentation process. As the whey itself has been obtained as a natural by-product from milk processing and is of negligible economic value, no emissions associated with agricultural processes have been considered. The input-output data for the analysis largely stems from own lab-scale experiments. EoL-treatment was not part of the examination. Hence, the net effect of avoiding emissions from the disposal of whey in comparison to EoL-emissions of PHA was also not included. An analysis of results by process step reveals that the fermentation stage has the biggest ecological footprint by far. This is mainly due to the high amount of electricity input required, the additional inputs heating energy and auxiliary materials contribute only to a much lesser extent. As a consequence, the ecological footprint of the whole process chain turned out to be more than four times higher than the ones obtained for each of the four fossil-based polymers. Against this background, the authors discussed opportunities for optimizing the fermentation technology. Two improvements are considered realistic: improving the PHA yield relative to the raw material for the same energy input and lowering the energy requirement per kg PHA to a level achieved in case of sugar cane. Under the condition of implementing both improvements, the authors demonstrate that the ecological footprint is reduced to a magnitude resembling the fossil-based polymers.

Dacosta (2014) investigates a scenario where PHB is produced from wastewater accruing in paper mills or the food industry. First, the organic material contained in the wastewater is fermented to fatty acids. Then, the resulting fatty acid stream are enriched with PHA producing bacteria in a selector and accumulated to PHB in an accumulation reactor. The accumulated product is concentrated and sent for PHB extraction and purification. Regarding these last two steps, three different technologies were proposed and tested. Another departure from conventional production pathways consists in the fact that a mixed instead of a pure bacterial culture was considered as input in fermentation. For the described processes, a cradle-to-gate ELCA was performed, however restricted to global warming potential and non-renewable energy use as impact categories. A further limitation is that no comparisons with conventional process routes as benchmarks were made, but merely a comparison of the different extraction/purification technologies. In the calculation, the emission savings resulting from the avoided process of wastewater treatment were subtracted. The results indicate that a scenario where dichloromethane (DSM) is used as a solvent in extraction is associated with larger environmental damages in terms of global warming and resource use than surfactant-hypochlorite or alkali-surfactant as inputs for the disruption of the bacterial cells. This is mainly due to the high utility consumption in the DSM scenario for hot water and hotdry air, the latter needed to improve solubility of the PHB by reducing water content. In comparing the other two scenarios, the outcomes are similar. In general, in addition to extraction, fermentation turns out to be another environmental hot spot, due to the steam use for heating the fermenters and the provision of growth nutrients.

Morgan-Sagastume et al. (2016) examine the opportunities of integrating PHA production into a municipal wastewater treatment plant. They compare five different treatment scenarios. The reference scenario is the standard scenario without PHA production and consistent of cleaning processes as well as cogeneration of heat and power from biogas and sludge residuals. The four alternative scenarios integrate PHA production by converting carbon-rich residuals from industrial or agricultural process into volatile fatty acids, which are then used to stimulate PHA accumulation of sludge obtained from municipal wastewater containing mixed bacteria cultures. The alternative scenarios differ slightly in specific assumptions regarding the nitrification and other sub-processes. The necessary data was gathered from a number of laboratory and pilot-scale wastewater treatment processes as well as from the literature. As impact categories for the LCA, global warming, eutrophication, acidification as well as photo-oxidant formation potential were investigated. In all of these categories, the standard wastewater treatment performs worse than the PHA production scenarios. First, this is due to the lower electricity use in the PHA scenarios, resulting from lower aeration requirements. Second, PHA scenarios produce less sludge and biogas as by-products that are incinerated, thus reducing emissions from combustion. The advantages remained when accounting for the opportunity of using the CHP generated from the biogas as a substitute for thermal and electric energy from natural gas. However, also in this case, a problem with the interpretation of the results is the apparent lack of functional equivalence between PHA-production and the reference scenarios.

Vogli et al. (2020) also investigate the environmental effects of using wastewater sludge as resource for PHA production. In their setup, the sludge first undergoes a pyrolytic pre-treatment to improve its fermentability. Then, it is used to generate volatile fatty acids through anaerobic digestion, which are then converted into PHAs with the help of a mixed bacteria culture. Finally, PHAs are extracted from the bacteria cells with the dimethyl carbonate method. Unlike other studies, the authors also consider the role of EoL-treatment, for which the assumption was made that the largest part of PHA will be incinerated, while the rest ends up in landfills. Regarding the use of energy sources, five different scenarios are compared, which differ both in external energy carriers and the utilization of the syngas produced in the pyrolysis step. An ELCA was conducted encompassing a wide range of 16 midpoint impact categories. In a cross-scenario comparison, it turns out that integrating the syngas as an energy carrier into the process can help to reduce GHG emissions, but the intensified sludge processing implies an increase of emissions of locally harmful substances associated with eutrophication and acidification at the same time. As additional benchmark processes, both PET and PP as fossil-based plastics and bio-PP and PLA were considered. For all these benchmarks, the conventional feedstocks and process routes were assumed (i.e. in case of PLA corn-based glucose). However, for these benchmarks only comparisons with respect to GHG emissions and non-renewable energy demand have been conducted. Concerning both categories, the considered PHA processes are on average comparable with the fossil-based polymers but perform slightly worse than the bio-based alternatives. This is different for the scenarios where the syngas is integrated as an energy carrier, in which the PHA processes clearly outperform the bio-based benchmarks.

Zarroli (2020) investigates the case of producing PHB from the wastewater accruing in mussel processing. The choice of this substrate was justified based on its high glycogen content, which is an appropriate feedstock for the generation of glucose. An ELCA was carried out incorporating not only global warming impacts and fossil depletion, but also acidification, eutrophication and ecotoxicity potential, which are especially relevant concerning emissions related to chemical use in residual wastewater treatment. The focus of the analysis is on the fermentation stage, for which a detailed inventory based on other sources was built up. In this regard, two scenarios were distinguished: one with mixed and one with pure bacterial culture. As a benchmark for comparison, no alternative pathways for the production of PHB were considered. Instead, the comparison is made with the alternative fate of the wastewater, i.e. an ordinary treatment process. Hence, the criterion of functional equivalence is in this case not fulfilled, which limits the comparability. Nevertheless, the author does undertake a comparative analysis of the results produced. It mainly reveals that the pure culture scenario is associated with tremendously higher damages than the mixed culture scenario in all impact categories considered. A main reason are the additional energy requirements associated with the sterilization activities needed to maintain pure cultures as part of the fermentation process. At the same time, mixed culture PHA production is shown to yield significantly lower impacts than standard wastewater treatment in all categories, especially with respect to human and freshwater ecotoxicity.

Solid organic waste

Kendall (2012) considers the environmental effects of producing PHB from organic waste collected from material recovery facilities. Precisely, the cellulosic fraction of organic material remaining as a residual after the separation of recyclable materials is used as a feedstock. It undergoes a hydrolysis process to obtain glucose molecules that enter the fermentation stage. The accumulated PHB is extracted, cleaned, and finally dried. Alternatively, the organics residuals would end up in landfills, where they contribute to the production of CO_2 and methane. The system boundaries take this fact into account by integrating these avoided emissions, while at the same time considering that also parts of the carbon entering the PHB production cycle will eventually be released as CO_2 during fermentation or the later degradation of the PHB product. The whole analysis has the form of a thought experiment, as all data for the single steps stem from external sources like existing studies and databases. As impact categories for the LCA, beside global warming and non-renewable energy consumption, acidification, eutrophication, and ozone formation potential were considered as well. The results are compared to the production of PHB from corn-based glucose involving standard processes. For this benchmark, estimated damages from land use change are explicitly accounted for. Against this background, the organic waste technology is shown to be associated with significantly lower energy requirements and also lower global warming potential than PHB from corn under all parameter sensitivities considered. However, the perspective is still limited, as the system boundaries do not include the alternative usage option of the organic residuals as energy sources in landfills or specific incineration facilities. Incorporating this into the analysis would require adding the emissions related to the production of the same amount of energy from conventional sources, which could significantly worsen the environmental balance. Moreover, no comparison with corn is made for local damage categories.

Shahzad et al. (2013) examine a PHA production chain based on the use of slaughterhouse waste. Solid slaughter by-products are partly chopped and hydrolysed to obtain an organic nitrogen source for the subsequent fermentation process. Other parts of the slaughter waste are heated and used to produce biodiesel and glycerol via transesterification. They constitute the carbon source of the fermentation process. The fermentation products are ultrafiltrated, homogenized and centrifuged to obtain pure PHA. High quality parts of the biodiesel are separated and thus represent a by-product of this PHA production process. For the environmental evaluation, no standard impact assessment method, but a unidimensional ecological footprint index (the same as in Koller et al. (2013) described above) was applied. Due to the high energy intensity of the slaughter processing, particular attention was paid to assumptions regarding the mix of energy carriers. The main scenario investigated was that of an energy mix representing the EU-27 average in 2009. As benchmark process routes for comparison, production of a fossil-based low-density polyethylene (LDPE) and an alternative processing of slaughterhouse waste to PHA solely based on renewable energies were chosen. PHA production based on the EU-27 energy mix yields a significantly lower total ecological footprint than the fossil-based benchmark. Quite unsurprisingly, the scenario based on renewable energies performed even better. However, in applying different country-specific energy mixes of nine European countries, it is demonstrated that even for the country with the lowest share of renewable energy in the energy mix there is still a reduction in the ecological footprint compared to the fossil-based benchmark to be noted. The major gains are measured for emissions to air, which is a direct result of the lower CO_2-intensity of bio-based plastics. However, given the lack of a benchmark producing PHA by means of conventional agricultural feedstocks, it remains open to what extent this result hints at a genuine advantage of waste as feedstock.

Biogas

Rostkowski et al. (2012) investigate the possibility of integrating PHB generation into a biogas production chain. Precisely, they consider the option of a two-way integration. Methane is used as a feedstock for PHB production, which could be captured from waste biogas by the waste sector. After the usage phase, the PHB is supposed to degrade again to methane in a landfilling facility, which in turn is made available as a feedstock for virgin PHB. In this way, a closed loop is conceived, whose environmental effects are analysed by the authors in a cradle-to-cradle analysis. An obvious environmental advantage of such a process is the reduction of methane losses in landfills and the associated global warming impacts. Moreover, like the other third generation processes, it avoids the emissions associated with extracting feedstocks from food plants. At the same time, utilizing the waste biogas involves its own environmental burdens, which in this study is modelled as the emissions of retrieving biogas from sewage sludge. Moreover, they account for the opportunity of using the excess cell material left after extracting the PHB from the bacterial cells as energy source. The energy requirements were not obtained based on own experiments but estimated based on a modelling approach for the scenario of production at industrial scale. LCAs were conducted for different PHB extraction methods, spanning quite a wide range of nine impact categories. It turned out that energy requirements are a crucial parameter not only for global warming, but also for local damage categories, and should be reduced in the future. Besides, the application of solvent extraction as extraction method causes additional toxic emissions, pointing against this method. Unfortunately, no direct reference comparisons with process routes for conventional feedstocks were made, limiting the informative value concerning environmental hotspots. The authors only make a comparison in terms of energy requirements with corn-based PHB, by referring to a value adopted from another study, suggesting that the total energy requirement per kg PHB is lower for biogas-PHB. However, it is not transparent to what extent this is based on compatible system boundaries and modelling techniques.

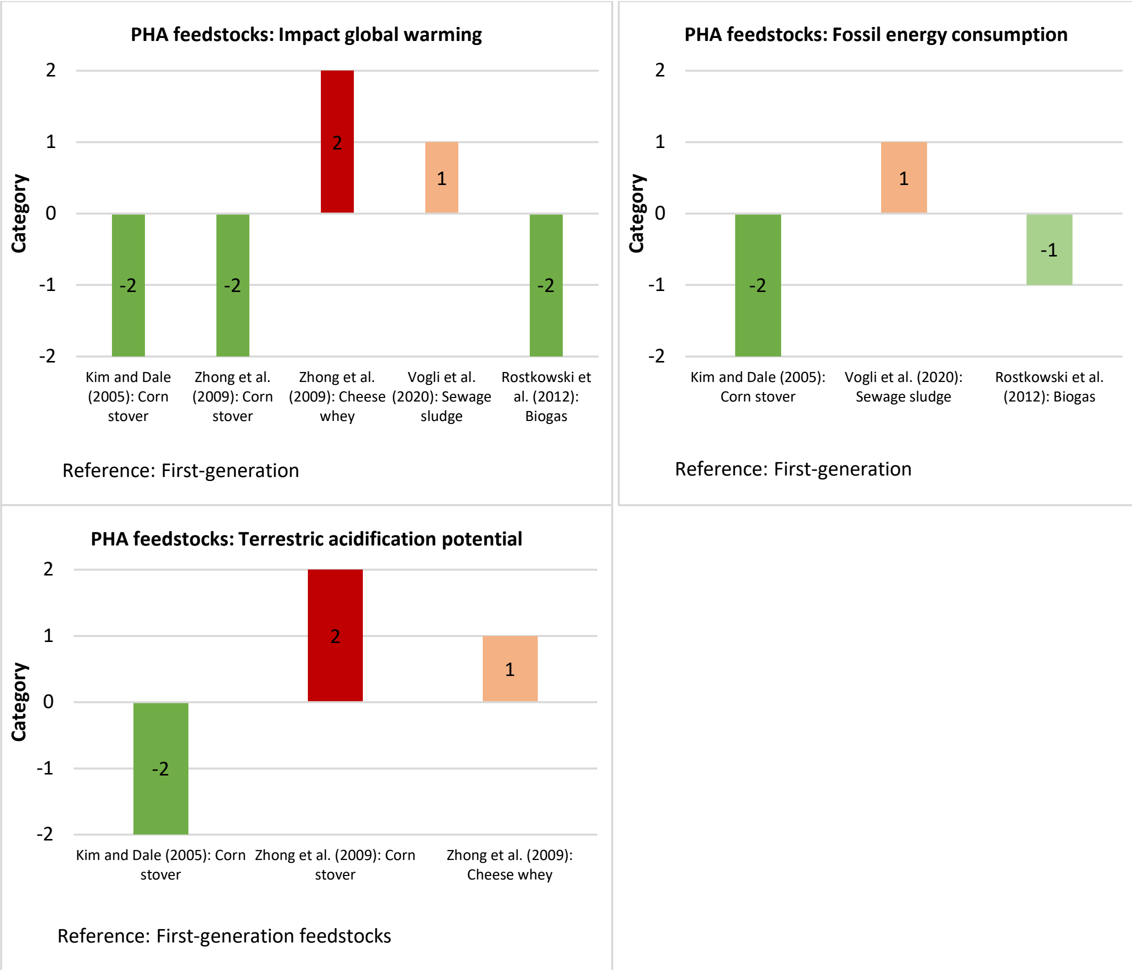
4.3.4 | Implications

For the category of PHA polymers, the literature on innovative feedstocks is more extensive than for the other polymers under consideration. Figure 4: ELCA literature results by impact category for PHA feedstocks presents a comparison of literature results for those impact categories for which at least three studies were available. Regarding plant material obtained as by-products in crop cultivation, the same arguments apply as in case of PLA (see 4.2.4). On the one hand, the possibility of allocating the emissions from cultivation among the co-products implies a reduction in the overall environmental burden compared to first-generation feedstocks. On the other hand, using plant materials like stalks and roots as bioplastic feedstocks implies giving up some of the ecosystem services these materials provide to the soil or as energy sources, implying that an ELCA should pay careful attention to the specific circumstances of cultivation.

With respect to third generation feedstocks, a quite large variety of different options have been so far subject to scrutiny. Complexity is further raised by the wide range of available options for processing technologies. Foremost, this concerns the use of different bacteria cultures in fermentation as wells as the method to extract the produced PHA from the bacterial cells. A clear focus of recent ELCA analyses is on the utilization of waste streams from industrial processes as well as from private households as substrates for feedstock extraction. As specific feedstocks, volatile fatty acids are mostly investigated. In some studies, the perspective taken is that of a comparison of alternative processing options for the same waste stream. As these alternative options have an almost non-existing or (in case of whey) very limited economic value, hence are not able to replace an emission-intensive production of valuable substitutes, it is not surprising that these studies consider the use of the waste stream for PHA production beneficial. Other studies are even more confined in restricting the comparison to alternative technology options for generating PHA from one and the same waste stream. Instead, insights in the eligibility of waste streams as feedstock substrates require comparisons with standard modes of PHA production. In this regard, the available evidence points to a high sensitivity towards processing conditions. In particular, the question to what extent by-products of the waste processing such as syngas or biodiesel are put to use as energy sources is shown to have a strong impact on the performance in terms of GHG emissions compared to PHA from first-generation feedstocks. This is necessary to compensate the high energy requirements, in particular with respect to the fermentation process.

Furthermore, just like in case of PLA, the mix of energy carriers underlying the electricity and steam consumption at local production sites is a critical parameter. For other locally oriented damage categories, corresponding comparisons are missing. This could partly distort the picture, as the processing of waste streams could potentially be associated with the release of harmful substances into local freshwater and soil. In this regard, Vogli et al. (2020) demonstrate that the treatment of by-products can cause additional local damages, which should be counterweighed against their GHG savings potential. Hence, in general, waste-based feedstocks are unlikely to dispel the basic trade-off between global and local environmental effects that lies at the heart of the current feedstock generation in bioplastic production.

Figure 4: ELCA literature results by impact category for PHA feedstocks



Source: own description; relative performance compared to reference feedstock (see 4.1)

5 | Conclusion

Our polymer-specific analysis of the ELCA literature has revealed a lot of common patterns, which allow us to formulate some general findings as guidelines for feedstock choices in LCAs from the present perspective. First and foremost, one should acknowledge that the ideal feedstock offering the optimal level of environmental friendliness in all relevant aspects is not in sight. Comparisons within and across feedstock generations need to balance different kinds of trade-offs. This primarily concerns the emission intensities of different production stages. Innovative feedstocks can offer a solution to the issues of land use and food competition associated with food industry inputs as bioplastic feedstocks. In this way, they can cause a reduction in emissions attributed to the primary cultivation stage. At the same time, however, their currently still low degree of technological maturity implies a high input intensity (especially of energy) in the refinery stages, as well as uncertainties regarding the optimal treatment methods for specific processes. Dependent on the underlying energy mix, this can seriously impair the environmental performance of refinery processes. For the future, technological improvements promise a reduction in emission intensity, but the present studies still lack evidence to what extent this will materialize. From an impact assessment perspective, this affects different environmental categories to a different extent. For instance, while the cultivation changes can imply emissions savings in the area of local harmful substances due to the avoidance of fertilizers etc., the higher energy intensity in refining can cause a surge of GHG-related categories. Hence, we can also talk about a trade-off in the dimensions of time and ecological focus.

Making informed decisions on feedstock use in this context requires to pay particular attention to the setting of system boundaries. The use of distinct feedstocks is associated with different opportunity costs as well as different by-products. The way in which alternative usage options and by-products are integrated into the system is revealed to play a crucial role for the overall environmental in the existing analyses. In particular, the option of utilizing by-products as energy sources for subsequent production steps, can substantially affect the performance with respect to greenhouse gases. This, in turn, requires that the local production conditions effectively allow for such an integration. At the same time, the specific location determines assumptions regarding the mix of sources used to generate the external energy. Hence, location choices for the single process steps can be critical, too. In specifying the process designs for an LCA, the critical decisions should thus always be made (and justified) against the background of the specific materials to be investigated.

6 | References

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7 | Appendix

Figure A 1: Papers on second- and third generation feedstocks for the production of PLA

Source	*Substrate*	*System boundaries*	*Assessment method*	*Impact categories*	*Reference material(s)*
Second-generation feedstocks					
Cellulosic feedstocks					
Adom & Dunn (2016)	Corn stover	Cradle-to-gate and cradle-to-grave-scenario	Own	CO_2-emissions	PLA from corn grains; Ethylene
Daful et al (2016)	Sugar cane bagasse	Cradle-to-gate	ReCiPe 2016	18 midpoint categories (i.a. global warming, ecotoxicity, acidification)	Fossil-based lactic acid
Ögmundarson et al. (2020)	Corn stover	Cradle-to-grave	ReCiPe 2016	24 midpoint categories (i.a. global warming, eutrophication, acidification); 3 endpoint categories (Human health, ecosystem quality, natural resources)	Lactic acid from corn grains
Third-generation feedstocks					
Liquid organic waste					
Harbec (2010)	Potato wastewater	Cradle-to-gate	IMPACT 2002+	4 endpoint categories (resource depletion, human health, ecosystem quality, climate change)	Lactic acid from corn grains

Broeren et al. (2017)	Potato wastewater	Cradle-to-gate	Mixed (CML baseline; ReCiPe midpoint; cumulative energy demand);	4 midpoint categories: GHG emissions, eutrophication, agricultural land use, non-renewable energy use	Lactic acid from corn grains; lactic acid from potato starch
Sea plants					
Helmes et al. (2018)	Green seaweed	Cradle-to-gate	ReCiPe 2008	18 midpoint categories (i.a. global warming, , eutrophication, acidification); 3 endpoint categories (Human health, ecosystem quality, natural resources)	Lactic acid from corn grains
Ögmundarson et al. (2020)	Microalgae	Cradle-to-grave	ReCiPe 2016	24 midpoint categories (i.a. global warming, eutrophication, acidification); 3 endpoint categories (Human health, ecosystem quality, natural resources)	Lactic acid from corn grains

Figure A 2: Papers on second- and third generation feedstocks for the production of PHA

Source	*Substrate*	*System boundaries*	*Assessment method*	*Impact categories*	*Reference materials(s)*
Second-generation feedstocks					
Cellulosic feedstocks					
Kurdikar et al. (2001)	Corn stover	Cradle-to-grave	Own	Global warming	LDPE, HDPE
Kim & Dale (2005)	Corn grains + corn stover	Cradle-to-gate	TRACI	4 midpoint categories (global warming, acidification, eutrophication, ozone formation	PHA from corn grains
Zhong et al. (2009)	Corn stover	Cradle-to-gate	Eco-Indicator 99	10 midpoint categories (i.e. global warming, acidification, ozone layer depletion, ecotoxicity)	PHA from corn grain
Third-generation feedstocks					
Liquid organic waste					
Koller et al. (2013)	Cheese whey	Cradle-to-gate	Sustainable Process Index (SPI)	Total ecological footprint	Four fossil polymers (PET, PE, PS, PP)
Dacosta (2014)	Wastewater from paper mill and food industry	Cradle-to-gate	Own	Global warming impact, Non-renewable energy use	None

Morgan-Sagastume et al. (2016)	Municipal wastewater	Cradle-to-gate	Mixed	4 midpoint categories (global warming, acidification, eutrophication, photo-oxidant formation)	None (comparison with alternative wastewater treatment processes)
Vogli et al. (2020)	Wastewater Treatment Sludge	Cradle-to-grave,	ILCD/PEF Recommendations	16 midpoint categories (i.a. global warming, acidification, eutrophication, ozone depletion)	PET, PP, bio-PP, PLA from corn grains
Zarroli (2020)	Industrial wastewater	Cradle-to-gate	ReCiPe midpoint; IPCC 2013	6 midpoint categories (i.a. global warming, acidification, eutrophication)	None (comparison with alternative wastewater treatment processes)
<u>Solid organic waste</u>					
Kendall (2012)	Mixed organic waste	Cradle-to-gate	Mixed	5 midpoint categories (global warming, primary energy use, acidification, eutrophication, ozone formation)	PHA from corn grains
Shahzad et al. (2013)	Animal residues (slaughtering waste)	Cradle-to-gate	Sustainable Process Index (SPI)	Total ecological footprint	PE
<u>Biogas</u>					
Rostkowski et al. (2012)	Biogas	Cradle-to-cradle	TRACI	10 midpoint categories (i.a. global warming, acidification, eutrophication, ozone depletion)	PHA from corn grains

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