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Assessing the Change in Environmental Impact Categories when Replacing Conventional Plastic with Bioplastic in Chosen Application Fields

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Biomass-derived bioplastic has potential to replace conventional plastic of fossil origin in plastics applications where sufficiently similar material properties can be achieved. The desired result of substitution would support the plastics industry with renewable resources and also lead to a reduction in fossil CO_2 emissions. These conditions are necessary for sustainable development and it is equally vital to prevent the shift of the environmental problem. Consequently, it is important to evaluate and consider environmental impacts holistically. For this investigation one option is the Life Cycle Assessment (LCA) method. Plastic is the collective term for polymeric materials, where the diversity and specifications of plastic products in production and application are enormous. In order to support the introduction of bioplastics into the market, it is important to focus on products that have a high potential for environmental sustainability when replacing conventional plastics. The objective of this study is to examine the application of a flexible LCA tool on four different examples, where bioplastic substitutes conventional plastic, to understand the change of environmental performances in the respective replacement. Setting the scope, samples from the following four plastic application fields are considered: Packaging, Building & Construction, Electrical & Electronic and Household. The change in the impact categories global warming potential GWP, acidification potential AP and eutrophication potential EP is taken into account. All assessed scenarios show a reduction in GWP and an increase in AP and EP. The product example from Building & Construction evaluating polyethylene, shows the highest potential of all examples to reduce GWP but simultaneously has the largest increase in AP and EP. This study confirms the concern of the problem shift for a bioplastic industry and encourages that environmental impacts should be made accessible in a transparent way, specifying assumptions and limitations of the quantitative outcome. These findings highlight the importance and need to consider the entire impact on the environment when implementing a novel technology that aims at sustainable development.

1. Introduction

Environmental issues, such as global warming, increase the need to be aware of the anthropogenic impact on our environment. Efforts are being made to look at and quantify these impacts through life cycle thinking and life cycle assessment (LCA). The LCA method can support decision-making by incorporating a more holistic view of technologies (at different stages of development) and their environmental impact. In aspirations to optimize the electrolysis process in the established chlor-alkali industry, an LCA concluded that a promising new approach using oxygen-depolarized cathodes had a poorer environmental performance than the commonly used membrane process when including upstream processes (Margallo et al., 2016). In a modern industry, an LCA study assessed options to reduce greenhouse gas emissions of a sugarcane biorefinery and highlighted the importance of including more impact categories for an environmental assessment. The Carbon Capture and Storage method was identified among other alternatives to have the highest reduction of the global warming potential GWP while simultaneously showing the highest impact in all other impact categories considered (Chagas et al., 2016). This underlines the importance of quantifying ideally all environmental impacts in all life cycle phases and impact categories. With global production of 335 Mt in 2016 (PlasticsEurope and EPRO, 2017), the plastics industry is inherently large and diverse, given the variety of applications. Bioplastics are

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plastic materials that derive from biomass and/or are biodegradable. There is potential to replace conventional plastic of fossil origin in application fields where sufficiently similar material properties are achievable with novel bioplastics (Shen et al., 2009). The desired outcome of such a replacement would base the plastic industry on renewable resources and furthermore lead to a reduction of fossil CO_2 emissions. In assessing the sustainability of bioplastics, one study concluded that bioplastics in other impact categories, in addition to GWP, are not naturally sustainable and that it is important to understand and consider them (Álvarez-Chávez et al., 2012). The review of life cycle assessments, which largely limited the assessment to GWP and energy consumption, in which the replacement of conventional plastic by bioplastics was investigated, gave different results (Yates and Barlow, 2013). Bioplastics are faced with higher production costs compared to conventional plastics, as latter are leading the way through multiyear optimization and economies of scale. A unique selling proposition of bioplastics is the sustainable aspect and therefore transparent information about the environmental performance in all categories is the key to the development and marketing of emerging bioplastics (Unilever PLC, 2017). To make the environmental impact more accessible to the plastics industry, it is recommended to use a LCA tool with a generic lifecycle modeled in the background to handle the complexity and diversity. Within the scope of this study, the potential change of environmental impacts in different application areas with different polymer materials is considered to assess the application of such a tool and find an application field with the highest potential to improve the environmental performance.

2. Method

For the purpose of the study, relevant samples are carefully selected and assessed by the flexible GaBi Envision LCA tool for bioplastics. This tool is capable of reporting the environmental impact of plastic products with a pre-defined LCA model when relevant key parameters are available that can be set within the tool. The background was developed to depict a typical life cycle of a conventional or bio-based plastic product, including the raw material extraction, polymer granulate production, compounding and conversion processes, product packaging, transportation and end-of-life scenarios (cradle-to-grave), as shown in Figure 1. After providing the relevant input parameters (including functional unit, scope, polymer granulate, compounding and conversion process parameters, additives, transportation, and end of life options) the life cycle is modeled accordingly within the tool and the results are calculated. The considered life cycle impact assessment categories are GWP (100 years), AP and EP from the CML 2001 – Jan. 2016 methodology. The modeling-principles for the pre-defined model and the included datasets from the databases GaBi Professional 2017, extension DB plastics VII 2017 and extension DB bioplastics XIX 2017 are compliant to the ISO standard for LCA (CEN, 2006). Four samples were selected to assess the potential change in environmental impact categories GWP, EP, and AP when replacing conventional plastics with bio-based plastics in a cradle-to-gate scope. Samples were carefully chosen from the most relevant application fields of plastics: Packaging 39.9 %, Building & Construction 19.7 %, Electrical & Electronic 6.2 % and Household 4.2 % (PlasticsEurope and EPRO, 2017). Some assumptions were made for these assessments of screening nature that are stated within each example in the results section. Additionally and beforehand a full life cycle scenario of the bio-PET bottle is calculated and the relative impacts of each life cycle stage are displayed, as shown in Figure 2. This hotspot information helps to understand the life cycle stages and their respective environmental impacts. For the scope of the study, the system boundary is described in Figure 1. For the cradle-to-grave life cycle of the bio-PET bottle, dashed lines represent the scope. The cradle-gate dotted lines describe the replacement examples and their system boundary. The additives are not included in these screening LCAs because the additives in the different products are not well enough known and their contribution from the mass point of view is relatively small. All scenarios considered, were calculated with a mixture of electricity generation representing the average in Europe. Electricity is required in the compounding and conversion processes and for taking into account the credit calculations from the incineration as the end of life scenario where energy is recovered from the waste treatment of plastics. For the transportation, distances were assumed since this highly depends on the granulate producer, compounder, converter and selling locations of the considered plastic product. The distances for all calculated scenarios were considered to be the same. The distance between the granulate production and the compounder was set to 500 km, from the compounder to the converter to 300 km, from the converter to the use phase to 400 km and from the collecting point to the end of life treatment to 70 km. The functional units were specific for each considered substitution example and are given within the tables 1-4.

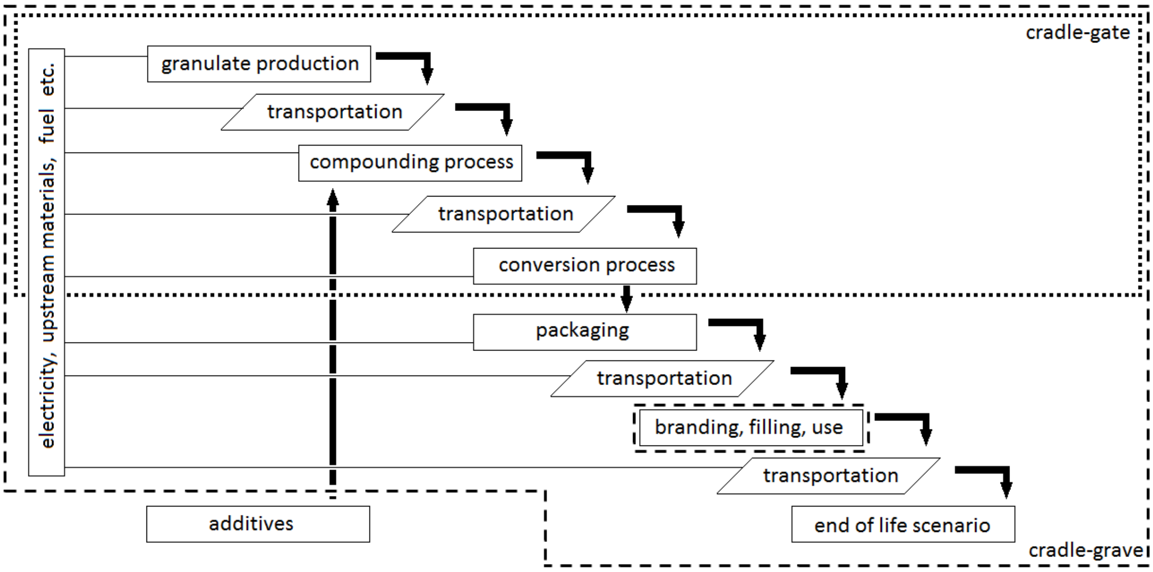

Figure 1: Description of the life cycle stages for a plastic product and the considered system boundaries for cradle-to-gate and cradle-to-grave scopes

3. Results and discussion

The cradle-to-grave life cycle of a PET-bio bottle is considered, and each life cycle stage and its environmental impacts are presented in a hotspot analysis to give information about the contribution of each life cycle stage to the overall result. Subsequently, the four substitution potential calculations, which are considered from cradle-to-gate, are presented.

3.1 Bio-PET bottle cradle-to-grave life cycle

Polyethylenterephthalat PET uses the monomer Bis(2-Hydroxyethyl)terephthalate, this is a product of a reaction between either terephthalic acid (PTA) and ethylene glycol or dimethyl terephthalate (DMT) and ethylene glycol. Ethylene glycol can be obtained from plant-based resources and makes up to 30 % of the PET product (Shen et al., 2009). The average from four datasets with different feedstocks and varying monomer production are taken for the calculation: PET partly from sugar cane via DMT, PET partly from sugar cane via PTA, PET partly from wheat via PTA and PET partly from corn via PTA. The functional unit is a palette of bottles (1840 pieces, 25 g each bottle) with PE-foil packaging weighting in total 46 kg empty bottles and 1.4 kg packaging. No additives are considered because their specifics are not well enough known within the scope of the study and their contribution from a mass point of view is low. From the database, a generic plastic compounding process is selected as well as generic plastic conversion steps: injection moulding and blow moulding. For the end-of-life, an incineration scenario with heat and energy recovery is selected. The environmental impact in the categories of GWP, AP and EP were calculated in a cradle-to-grave analysis for bio-PET bottles life cycle phases and the results are described in Figure 2.

3.2 Substitution potential calculations

Two kinds of bioplastics are included in the replacement example inventories. The bioplastics within the example of the PET bottle and the PE pipe pertain to so-called drop-in bio-based plastics (same polymer but the monomer is derived from renewable resources). In the PLA examples of household cutlery and computer mouse shells, a novel polymeric material is considered. For the latter, the assumption of similar product properties and the same parameter settings for the compounding and conversion process steps were necessary for the scope of this study. The functional units were set for each substitution example individually and are found in the Tables 1-4.

PET bottle example in drink packaging

For the Bio-PET plastic bottle example, the LCA parameters are given in Table 1. The same bio-PET as in the hotspot calculations is considered. The results show a decrease in GWP and an increase in AP and EP.

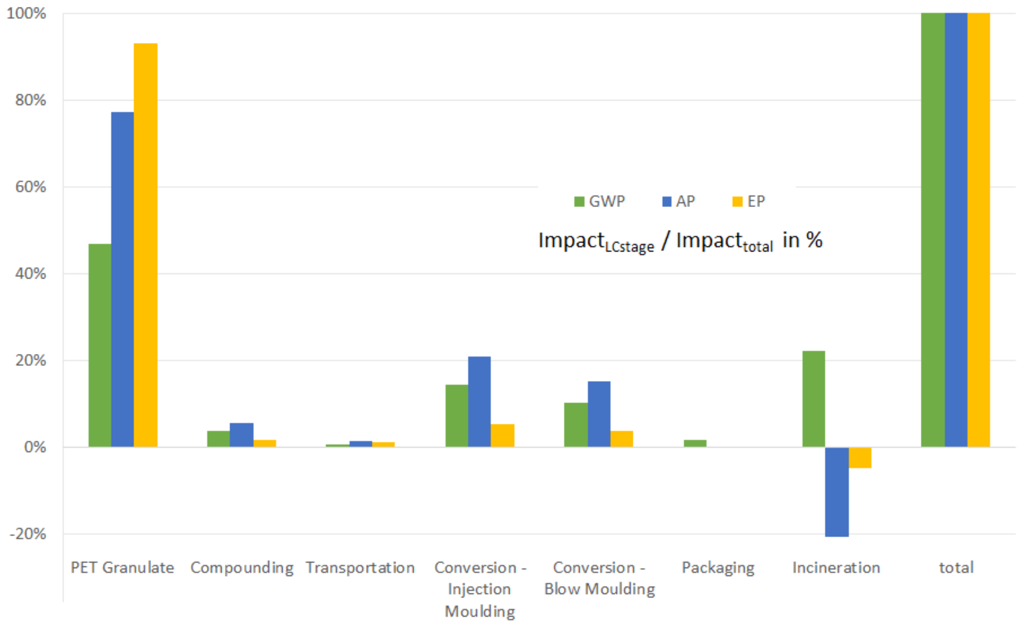

Figure 2: Environmental impacts of the life cycle stages for bioPET (30 %) bottles

Table 1: LCA results and parameters for the example of bio-PET replacing conventional PET

Impact category	GWP [kg CO_2 eq.]	AP [kg SO_2 eq.]	EP [kg Phosphate eq.]
Bio-PET	204	0.615	0.194
PET	221	0.434	0.046
Parameters:	Scope	*Cradle-gate*	*Granulate production to conversion process*
	Functional unit	*1 pallet of empty bottles*	*1,840 pieces, 25 g each*
	Compounding	*generic process, no additives considered*	
	Conversion	*generic plastic injection moulding and blow moulding parameters*	
	Transportation	*to compounding: 500 km / conversion: 300 km*	*by truck*

PE pipes example in building & construction

Ethylene (the monomer for Polyethylene PE pipes) is conventionally produced from fossil naphtha. It can also be produced through dehydration of ethanol that is derived from biorefineries (Shen et al., 2009). For these calculations, the average Bio-PE process data from wheat, sugar cane and corn biorefinery are considered. The resulting environmental impacts and the considered parameters are given in Table 2.

Table 2: LCA results and parameters for the example of bio-PE replacing conventional PE

Impact category	GWP [kg CO_2 eq.]	AP [kg SO_2 eq.]	EP [kg Phosphate eq.]
Bio-PE	325	12.5	7.45
PE	1.15E03	2.73	0.287
Parameters:	Scope	*Cradle-gate*	*Granulate production to conversion process*
	Functional unit	*100 meter of PE-pipes*	*diameter 200 mm, PN4, 4.8 kg/m*
	Compounding	*generic process, no additives considered*	
	Conversion	*generic plastic extrusion profile parameters*	
	Transportation	*to compounding: 500 km / conversion: 300 km*	*by truck*

PLA/PVC disposable cutlery example in household goods

The monomer for Polylactic acid PLA is fermented from renewable feedstocks (Shen et al., 2009). Polyvinylchlorid disposable plastics can be replaced with PLA. The results and the respective parameters are given in Table 3.

Table 3: LCA results and parameters for the example of PLA replacing conventional PVC

Impact category	GWP [kg CO_2 eq.]	AP [kg SO_2 eq.]	EP [kg Phosphate eq.]
PLA	880	3.58	0.725
PVC	1.60E03	2.42	0.376
Parameters:	Scope	*Cradle-gate*	*Granulate production to conversion process*
	Functional unit	*20000 disposable cutlery pieces*	*spoons each 5.15 g*
	Compounding	*generic process, no additives considered*	
	Conversion	*generic thermoforming parameters*	
	Transportation	*to compounding: 500 km / conversion: 300 km*	*by truck*
Assumptions:	Product properties	*assumed to be identical, strongly suggested to further assess in a more detailed assessment*	
	Compounding and Thermoforming	*Assumed to be identical, however different polymers most likely need different process parameters*	

PLA/PP example considering a shell of a computer mouse in electrical & electronic

Specific PLA plastics have similar properties to polypropylene PP (Shen et al., 2009), a fossil-based polymer. In this example, PLA replaces polypropylene PP for a computer mouse shell. The results and parameters are given in Table 4.

Table 4: LCA results and parameters for the example of PLA replacing conventional PP

Impact category	GWP [kg CO_2 eq.]	AP [kg SO_2 eq.]	EP [kg Phosphate eq.]
PLA	8.64	0.054	0.009
PP	15.2	0.036	3.72E-03
Parameters:	Scope	*Cradle-gate*	*Granulate production to conversion process*
	Functional unit	*100 computer mouse shells*	*each 50 g*
	Compounding	*generic process, no additives considered*	
	Conversion	*generic plastic injection moulding parameters*	
	Transportation	*to compounding: 500 km / conversion: 300 km*	*by truck*
Assumptions:	Product properties	*assumed to be identical, strongly suggested to further assess in a more detailed assessment*	
	Compounding and Injection moulding	*Assumed to be identical, however different polymers most likely need different process parameters*	

3.3 Analysis and summary

Looking at the whole life cycle of the BioPET Bottle the BioPET granulate production is the biggest contributor to all three impact categories. Secondly, the conversion steps and the incineration scenario are relevant life cycle stages. The credits from the incineration are recognized within the total calculation of the incineration step, having higher credits than impact, which leads to a negative impact percentage, as shown in Figure 2. The transportation, compounding, and packaging are rather small contributors to the selected environmental impacts. In Table 5 the environmental impacts of the bio-based plastic within each example are put in relation to the environmental impacts of each respective fossil alternative option to analyze the changes. All results show a reduction of GWP while increasing AP and EP. The renewable resource options considered agriculture processes where AP and EP are more likely to be affected. When utilizing plant-based resources the fixation of CO_2 in the feedstock production is leading to a reduced GWP. Within this screening assessment, the total numbers have to be seen with caution, considering the assumptions and the aim of a screening LCA within the comparative scope of this study. These results are not fit for a comparison outside their respective example.

This LCA tool for bioplastics showed that it can depict very different plastic applications and materials. It provides first results to increase the awareness of the environmental impacts and can be seen as a basis for further assessments.

Table 5: LCA results of the bio-based plastic relative to the fossil-based plastic in the four examples

Substitution	Rel. impact of the bio-based option to the fossil option within		
	GWP [kg CO_2 eq.]	AP [kg SO_2 eq.]	EP [kg Phosphate eq.]
PET → BioPET	93 %	142 %	422 %
PE → BioPE	28 %	461 %	2.60E03 %
PVC → PLA	55 %	148 %	193 %
PP → PLA	57 %	150 %	242 %

4. Conclusion

The results show that the environmental impacts show similar trends within each impact category when switching from conventional plastics to bioplastics and differ in extent depending on the application field. Sustainable development is a complex issue and the ambiguous results show that simply choosing renewable materials is a start but not the final solution to environmental problems such as global warming. Depending on the application and the material used, bioplastics can show advantages over conventional plastics in some environmental impact categories. While plant-based products reduce GWP, the required agricultural processes tend to increase typical impact categories as AP and EP. Considering the high impact of the granulate production, recycling of polymers is promising to further reduce the environmental impacts by reducing the amount of required virgin material, therefore the ability of a polymer for recycling is important to consider for further investigations. The GaBi Envision bioplastic tool makes the environmental impacts for the diverse field of plastics more accessible. However these LCA calculations are of a screening-nature and have to be considered and communicated with all assumptions (e.g. equal product properties) and limitations (e.g. no use phase, different production industrialization degrees).

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