ENVIRONMENTAL FACTSHEET: **POLYHYDROXYALKANOATES**

PRODUCT INFORMATION

Polyhydroxyalkanoates (PHAs) are biobased, biodegradable and biocompatible polymers. Up to now there are 150 different monomer compositions known for PHAs (such as: polyhydroxybutyrate PHB and polyhydroxyvalerate PHV), resulting in a high variety of properties and applications. PHAs can replace currently used petrochemical polymers in coatings and packaging. Owing to their biocompatibility and biodegradability, PHAs can also be used for medical purposes.

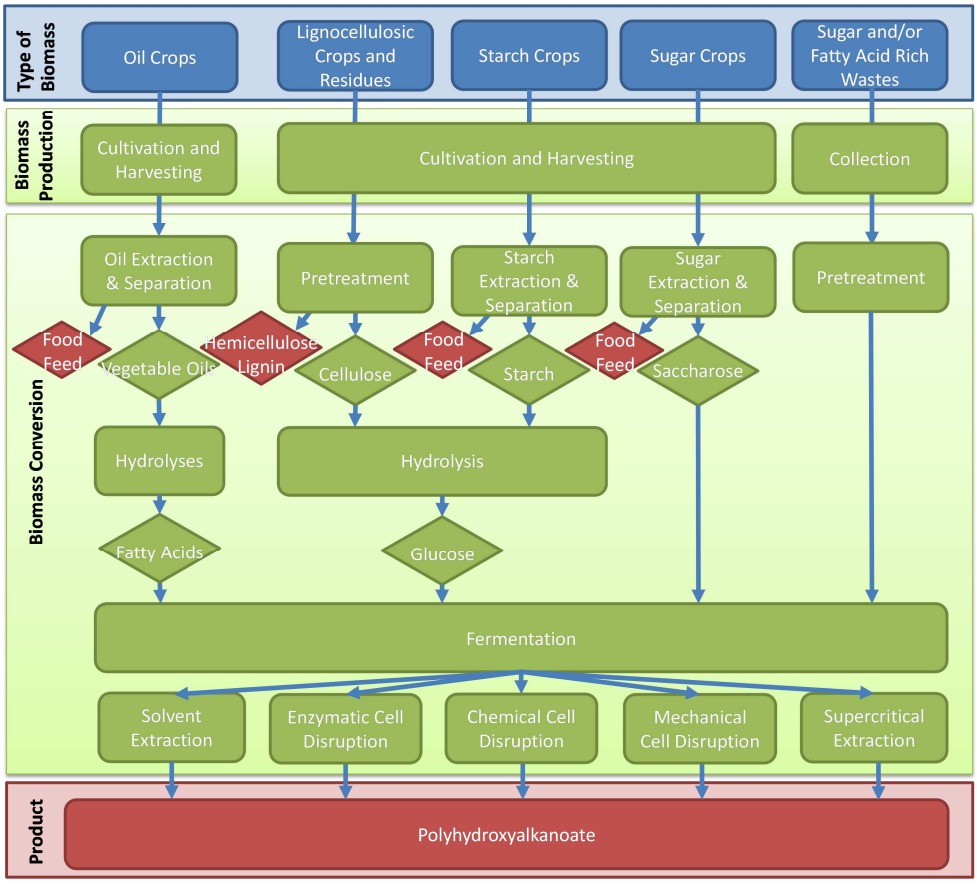

Figure 1. *PHA production chains*

PHAs can be produced via fermentation of sugars, fatty acids and wastes, see Figure 1. Different types of microorganisms are able to synthesise PHAs. These polymers are accumulated as intracellular granules during nutrient depletion phases or during an abrupt increase of carbon supply. They are normally produced in two fed-batch steps (a growth step and a polymer accumulation step). The type of used microorganisms and the operation conditions influence the molecular weight of PHAs, which may range from 2×10^5 to 3×10^6 Da [1]. Most commercially produced PHAs are synthesised by pure bacterial cultures using simple carbon sources (such as sugars and fatty acids).

However, PHAs production costs are high and research is targeting the development of production processes using: (1) lower cost raw materials (such as wastes or unrefined materials), (2) mix bacterial cultures and (3) novel solutions to obtain higher yields. After fermentation the microbial biomass should be separated from the fermentation broth and the synthesised polymer must be extracted from inside the cells. The extraction is typically done using organic solvents (e.g. ethanol, acetone, chloroform). The large quantities of solvents needed for the extraction decrease the environmental performance of PHAs production and increase costs. Various alternatives are being studied to alleviate or avoid the setbacks of solvent extraction, such as: (1) supercritical fluids, where supercritical CO_2 acts as solvent at high pressures; (2) disruption of cell materials to release PHA, using enzymatic, chemical or mechanical (high-pressure homogenisation, ultrasonic disruption and bead mills) procedures. Other methods are also being developed to facilitate PHA extraction/separation, such as: (1) dissolved air floatation to separate PHA from the other components of the enzymatic cell disruption; (2) use of genetically modified microorganisms with easier releasing PHA properties.

PHA can also be produced by plants such as switchgrass, where PHA is produced in the plant cells. After cultivation and harvesting, switchgrass needs to be dried and PHA can be extracted from the plant tissues.

The maturity of various PHAs production technologies is summarised in Figure 2. The lignocellulosic pathway appears to be the least advanced production system, while production pathways using sugars from sugar/starch crops or fatty acids from oil crops are already commercially available.

Technology Readiness Levels

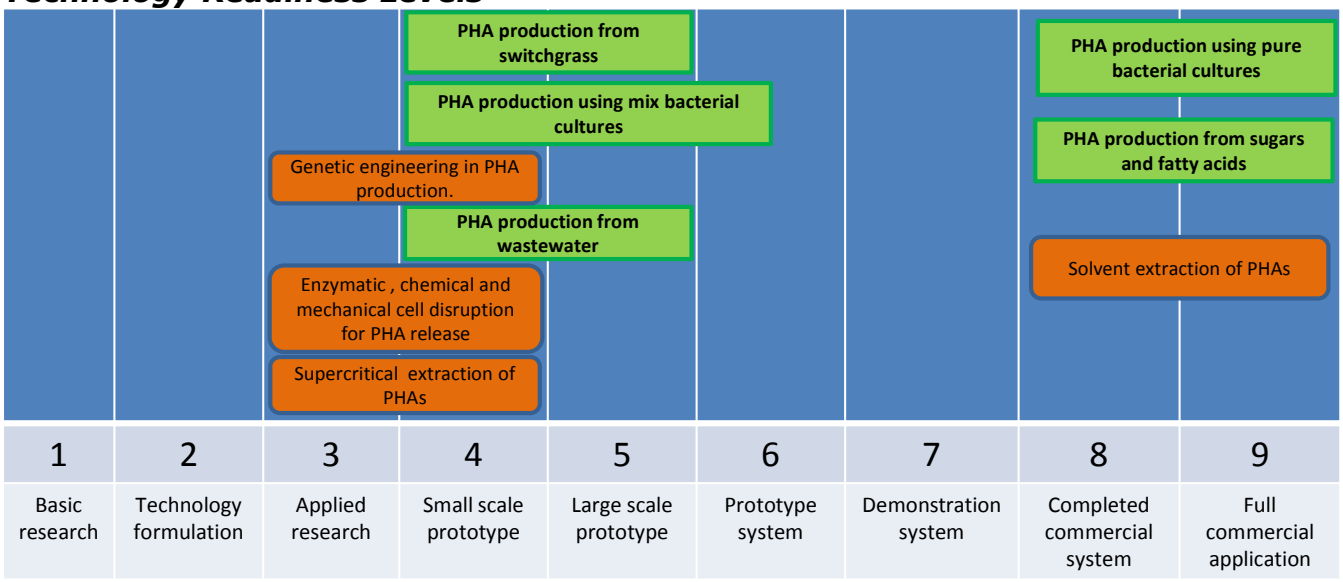

Figure 2. *Technology readiness levels for PHA production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. PHAs are biodegradable and biocompatible polymers with similar properties of the commonly used fossil based polymers. **S2.** Due to their low permeability to oxygen, PHA polymers are suitable for food packaging.	**W1.** PHAs production costs are higher compared to fossil polymers.
O1. The use of PHAs has been approved for booth food contact material and surgical sutures. **O2.** The new developments in PHA extraction and yields, and use of wastes could decrease PHA production costs.	**T1.** Biomass availability, competition with food and feed. **T2.** Cost of raw material.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of PHA is summarised in Table 1 based on the available relevant LCA data for different feedstocks: corn, sugar cane, lignocellulosic wastes (a less mature technology, but with potential for improvements) and oil crops. Most of the presented values refer to the cradle to gate (see Figure 3) LCA approach.
The most widely reported impact categories are climate change, land use, primary energy and non-renewable energy. Few or no results were found for the remaining impact categories of the environmental sustainability assessment methodology developed in the context of this project (see explanatory document).

System boundaries of the environmental assessment

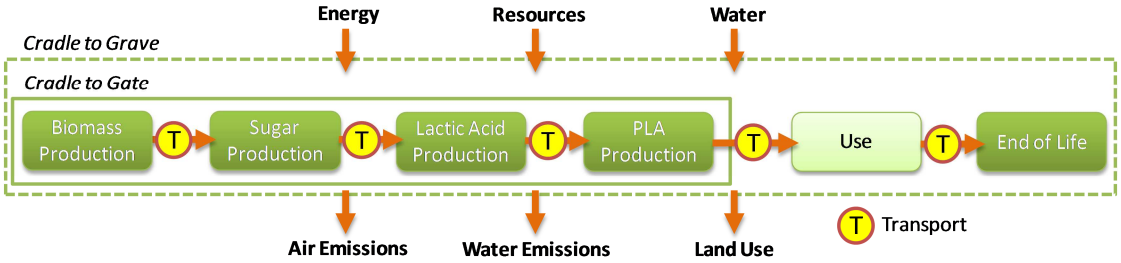

Figure 3. *LCA system boundaries for PHA production and end-of-life*

1. Cradle to gate: includes the resources extraction (energy, materials and water), transport and the production steps until the gate of the PHA factory. **2. Cradle to grave:** additionally to the cradle to gate activities, this system includes the transport and distribution of the product, the use of PHA and its end-of-life.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of PHA in a cradle to gate system

Raw material input (feedstock)	Corn	Sugar Cane	Lignocellulosic wastes	Soybean	Rapeseed
Allocation/substitution	A($-m), S	A($), S	A($-m), S	m	A($), S
Geographical coverage	US, Europe	South Africa, Brazil	US, Europe	US	Europe
References	[1,4,5,6]	[1,3]	[1,2,5,7]	[4,7]	[1]
Impact categories from Environmental Sustainability Assessment methodology					
Climate change (kgCO_2eq)	(-2.3)1 (3.0-4.2)	(0.1-1.1)3	(1.3-5.1)	0.261	(5-6.9)5
Ozone depletion (kg CFC-11 eq)	N.A	$1.7E^{-7}$ [3]	N.A	N.A	N.A
Acidification (mol H^+eq)	2.14 [4]	N.A	0.81 [4]	N.A	N.A
Marine water eutrophication (kgNeq)	$1.9E^{-3}$ [4]	N.A	$1.9E^{-3}$ [4]	N.A	N.A
Freshwater eutrophication (kgPO_4eq)	N.A	$5.2E^{-3}$ [3]	$5.4E^{-4}$-$5.0E^{-3}$ [5]	N.A	N.A
Additional impact categories					
Fresh water ecotoxicity for (kg 1,4-DBeq)	N.A	0.106 [3]	N.A	N.A	N.A
Human Toxicity - non cancer effects (kg 1,4-DBeq)	N.A	0.86 [3]	N.A	N.A	N.A
Photochemical ozone formation (kg C_2H_4eq)	N.A	$7.8E^{-4}$ [3]	$3.1E^{-3}$-$4.9E^{-3}$ [5]	N.A	N.A
Land use (m^2)	(3.8-4.0) [1]	(4.0-4.1) [1]	(1.6-1.7)[6] [1]	N.A	(11.4-18.8)[5]
Terrestrial ecotoxicity (kg 1,4-DBeq)	N.A	$9.0E^{-3}$ [3]	N.A	N.A	N.A
Marine ecotoxicity (kg 1,4-DBeq)	N.A	1290 [3]	N.A	N.A	N.A
Acidification (kg SO_2eq)	N.A	$2.5E^{-2}$ [3]	$1.6E^{-2}$-$2.8E^{-2}$ [5]	N.A	N.A
Abiotic depletion (kg Sb eq)	N.A	$2.2E^{-2}$ [3]	N.A	N.A	N.A
Primary energy (MJ)	(144.2-161.0) [1]	(161.0-183.8) [1]	(148.4-170.7)[1]	N.A	(164.1-171.5)
Non-renewable energy (MJ)	(2.5)2 (69.0-111.6)4	(33.4-59.0)3	(61.6-78.2)4	50	(60.9-109)

Note: N.A. not available. A=Allocation ($-economic; E-energy; m-mass). S=Substitution. SE=System expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [9] and the ReCiPe normalisation factors (see explanatory document).

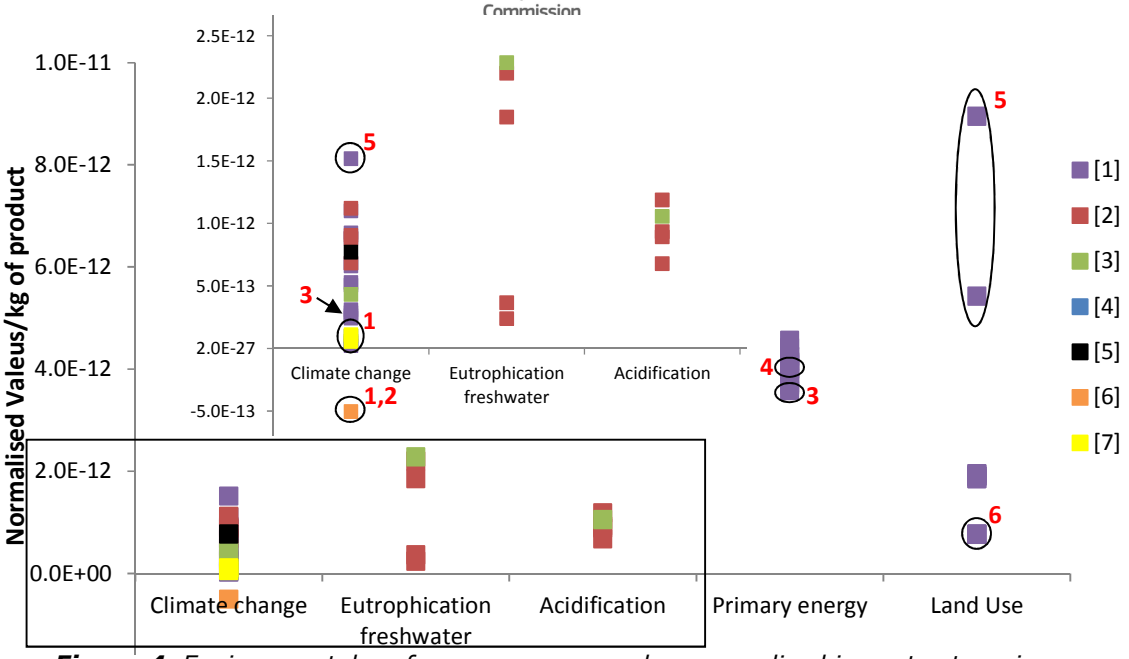

Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table1 and Figure 4):

1. The authors of references [4,6,7] considered the avoided emissions of CO_2 as a credit (to account for the carbon uptake during biomass growth), which explains the low climate change impact values;
2. In addition, the authors of reference [6] considered the burning of corn stover and fermentation residues to generate electricity and steam, which explains the low consumption of non-renewable energy and also lower climate change impacts. When this is not considered, the non-renewable energy results can increase up to 111.6 $MJ/kg_{polymer}$;
3. The lowest values found for climate change and non-renewable energy demand were obtained for the production of PHAs from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [2] for the energy surplus, generated from bagasse burn;
4. The authors of reference [2] account for the burning of lignin-rich waste [obtained during the pre-treatment (hydrolyses) (see bioalcohols via fermentation factsheet) of corn stover] to produce power and heat. This results in decreased impacts in non-renewable energy demand and climate change categories;
5. Higher climate change and land use impacts were found for the rapeseed pathway due to its lower productivities;
6. Land requirements for PHA production based on corn stover are lower compared with those based on corn, sugar cane and rapeseed. This is due to the economic allocation applied [2], which assigns a lower value to corn stover than corn kernels.

REFERENCES / FURTHER INFORMATION

[1] Akaraonye et al., 2010. J Chem Technol Biotechnol, 85: 732-743.
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