ENVIRONMENTAL FACTSHEET: **POLYLACTIC ACID**

PRODUCT INFORMATION

Polylactic Acid (PLA) is a biodegradable and biocompatible thermoplastic. It is used for the production of packaging, plastic films, bottles and fibres, and in medical applications. PLA is produced from the chiral compound Lactic Acid (see lactic acid factsheet[1]). It can be synthesised in three stereochemical forms: poly-L-lactic acid (usually a semicrystalline polymer), poly-D-lactic acid (usually a highly crystalline polymer), and poly-DL-lactic acid (an amorphous polymer).

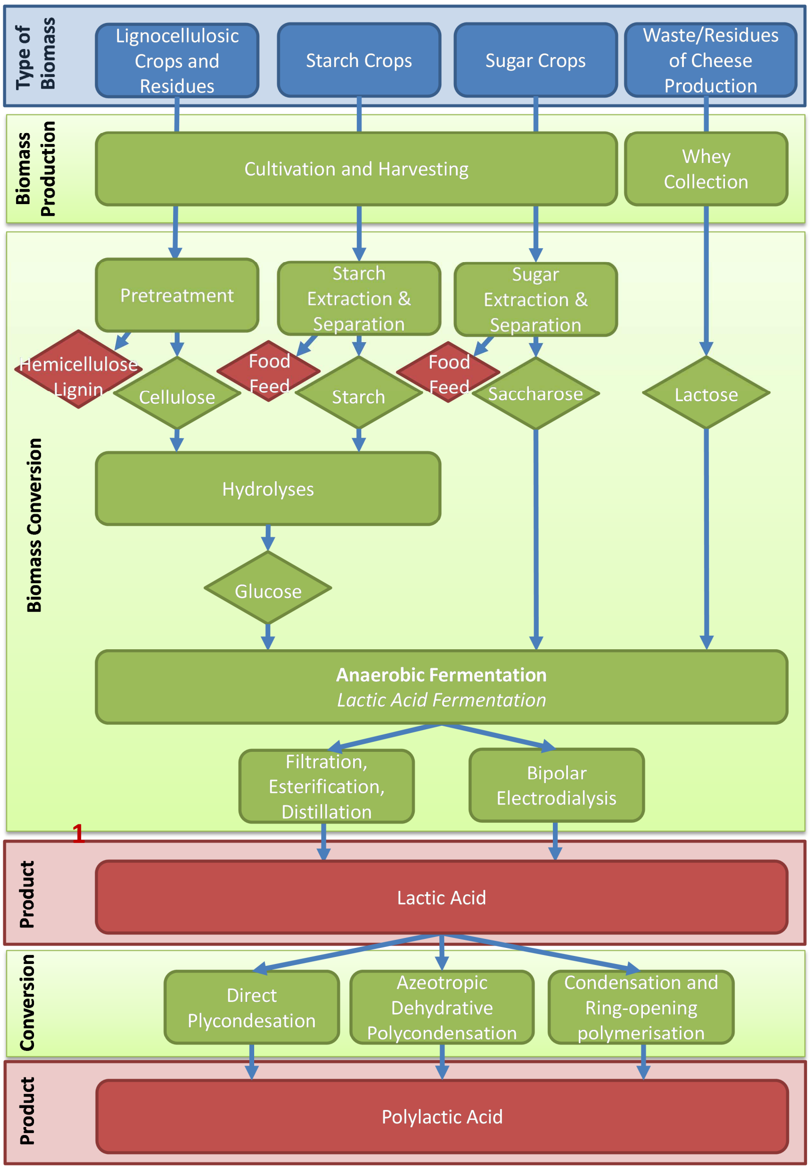

Figure 1. *PLA production chains*

PLA manufacturing requires the production of two intermediary products: lactic acid and sugars (such as glucose, saccharose or lactose), see Figure 1. Lactic acid (see lactic acid factsheet[1]) is produced from fermentation of sugars which are obtained from processing different types of biomass (e.g. lignocellulosic materials, starch crops, sugar crops and whey). The maturity of various PLA production technologies is summarised in Figure 2. The use of lignocellulosic materials appears as the least advanced production pathway. While the use of sugars from starch or sugar crops is fully commercially available.

PLA is synthesised from lactic acid mainly in two ways: a) direct polycondensation of lactic acid and b) ring-opening polymerisation of lactide. The latter is the most common way of producing high molecular weight PLA and involves condensation of lactic acid to the cyclic diester lactide and conversion of lactide to PLA by catalytic ring-opening polymerisation. The direct polycondensation of lactic acid produces only low molecular weight polymers. Higher molecular weights can also be produced by: chain coupling agents (after direct polycondensation) or by azeotropic dehydrative polycondensation of lactic acid using azeotropic solvents.

In addition to the above methods, sequential melt and solid polycondensation was also proposed to increase the molecular weight of PLA polymer. This process includes two polymerisation steps performed at different temperatures: above melting point and below melting point, without solvents.

Technology Readiness Levels

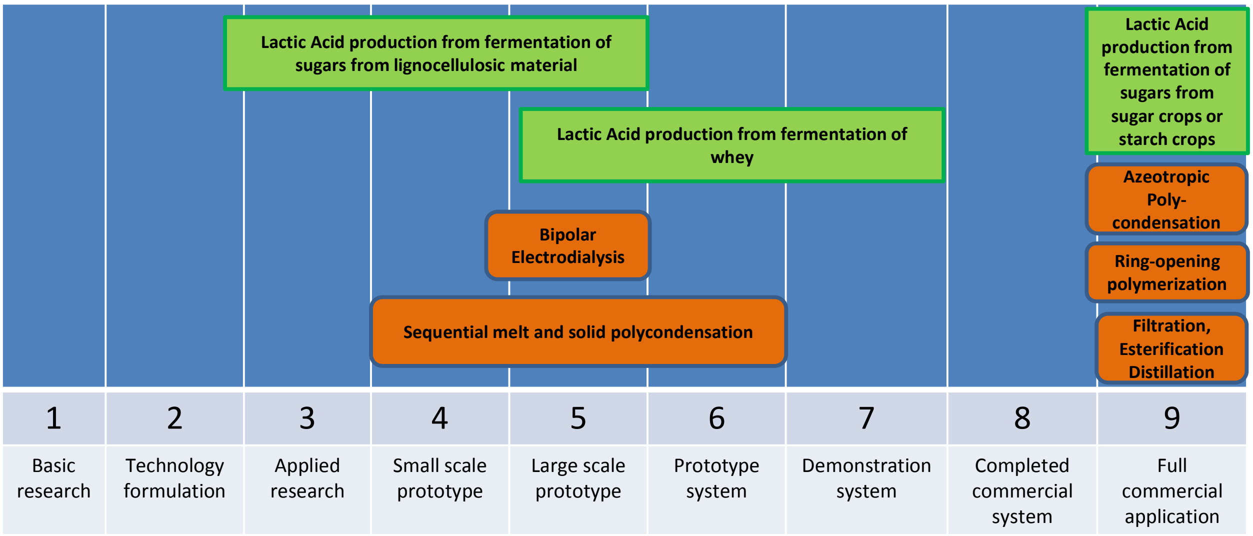

Figure 2. *Technology readiness levels for PLA production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. PLA is a biodegradable and biocompatible polymer, allowing for high added value applications (such as medical). **S2.** Due to its biodegradability it can be used for disposable packaging.	**W1.** PLA production costs are high compared to fossil polymers. **W2.** PLA thermal and gas permeability are lower compared to fossil polymers.
O1. Developments of new catalysts and melt polymerisation processes would reduce PLA production costs. **O2.** The possibility of producing lactic acid from waste/residues could decrease production cost.	**T1.** Biomass availability, competition with food and feed. **T2.** Cost of feedstock: lactic acid.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of PLA is summarised in Table 1 based on the available relevant LCA data for PLA production through: 1. Ring opening polymerisation; 2. Lactic acid purification using neutralization, filtration, esterification and distillation (see lactic acid factsheet[1]). The majority of the values refer to cradle to gate (see Figure 3) LCA approach. When cradle to grave is considered [1] the climate change results can increase up to 55% depending on the end-of-life scenario considered.

The most commonly 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 factsheet).

System boundaries of the environmental assessment

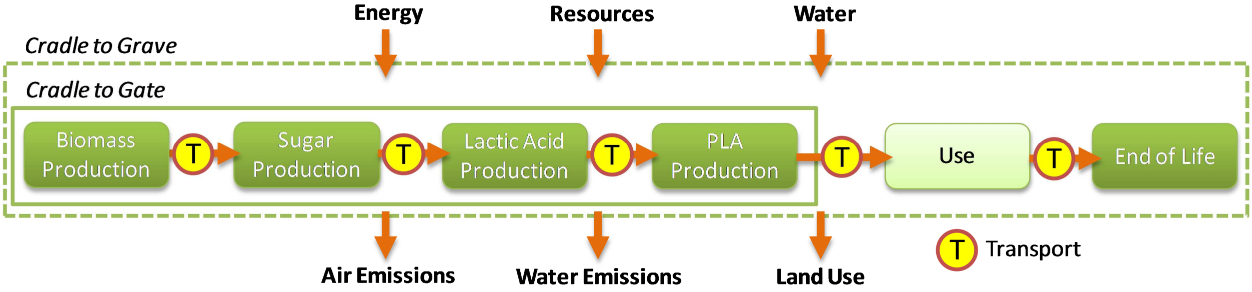

Figure 3. *LCA system boundaries for PLA production and end-of-life*

1. Cradle to gate: includes the resources extraction (energy, materials and water), transport and the production steps until the gate of the PLA 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 PLA and its end-of-life.

Environmental assessment: settings & impacts

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

Raw material input (feedstock)	Corn	Sugar Cane	Corn stover
Allocation/substitution	A($-m), S	A($), S	A($), S
Geographical coverage	USA, Europe	Brazil, Thailand	USA, Europe
References	[1-7]	[1,8]	[1-2]
Impact categories from Environmental Sustainability Assessment methodology			
Climate change (kgCO$_2$eq)	(0.3)***1*** (1.1-3.2)	(-0.1-1.0)***2***	(0.5-1.5)
Ozone depletion (kg CFC-11 eq)	(9.4E^{-8}-3.6E^{-7}) [4,6]	N.A	N.A
Freshwater Ecotoxicity (CTUe)	6.5 [4]	N.A	N.A
Human Toxicity - cancer effects (CTUh)	1.5E^{-7} [4]	N.A	N.A
Human Toxicity - non cancer effects (CTUh) and (kg 1,4-DBeq)	7.5E^{-8} [4] (CTUh)	8.5E^{-3} [8] (kg 1,4-DB$_{eq}$)	N.A
Particulate Matter/Respiratory inorganics (kgPM2.5eq)	4.4E^{-3} [6]	N.A	N.A
Acidification (mol H$^+$eq)	0.62 [4]	N.A	N.A
Marine Eutrophication (kgN$_4$eq)	2.5E^{-2} [4]	N.A	
Freshwater Eutrophication (kgPO$_4$eq)	(1.8E^{-4}-7.5E^{-3}) [5-7]	5.0E^{-3} [8]	N.A
Resource depletion – water (kg of water)	(49-69.3) [2,3]	N.A	N.A
Additional impact categories			
Photochemical ozone formation (kg C$_2$H$_4$eq)	1.0E^{-3} [7]	3.4E^{-3} [8]	
Acidification (kg SO$_2$eq)	(1.2E^{-2}-3.8E^{-2}) [5-7]	2.1E^{-2} [8]	N.A
Respiratory Organics (kg C$_2$H$_4$eq)	4.3E^{-3} [6]	N.A	N.A
Terrestrial Eutrophication (kgPO$_4$eq)	1.4E^{-2} [7]	N.A	N.A
(Land use) (m^2)	(1.7-2.8) [1,3,7]	(1.8-2.8)	(0.6-1.7)***3***
Primary energy (MJ)	(58.4)***1*** (65.8-97.4) [1-3,5-7]	(86-105.5)	(81.2-99.4) [1]
Non-renewable energy (MJ)	(27.2)***1*** (32.4-60.8) [1-3,5-7]	(21.4-32.9)***2***	(29.2)***1*** (33.8-45.3)***4***

Notes. N.A. not available. A=Allocation ($-economic; E-energy; m-mass). S=Substitution. SE=System expansion. From references [5] and [6] the environmental results presented in the Table 1 refer only to the PLA production and upstream extraction and production steps. The production of drinking water bottles [5] or the clamshell containers [6] was excluded. The weight of PLA in 1000 bottles was 12.58 kg [5] and the weight of 1000 clamshell containers was 30.54 kg.

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

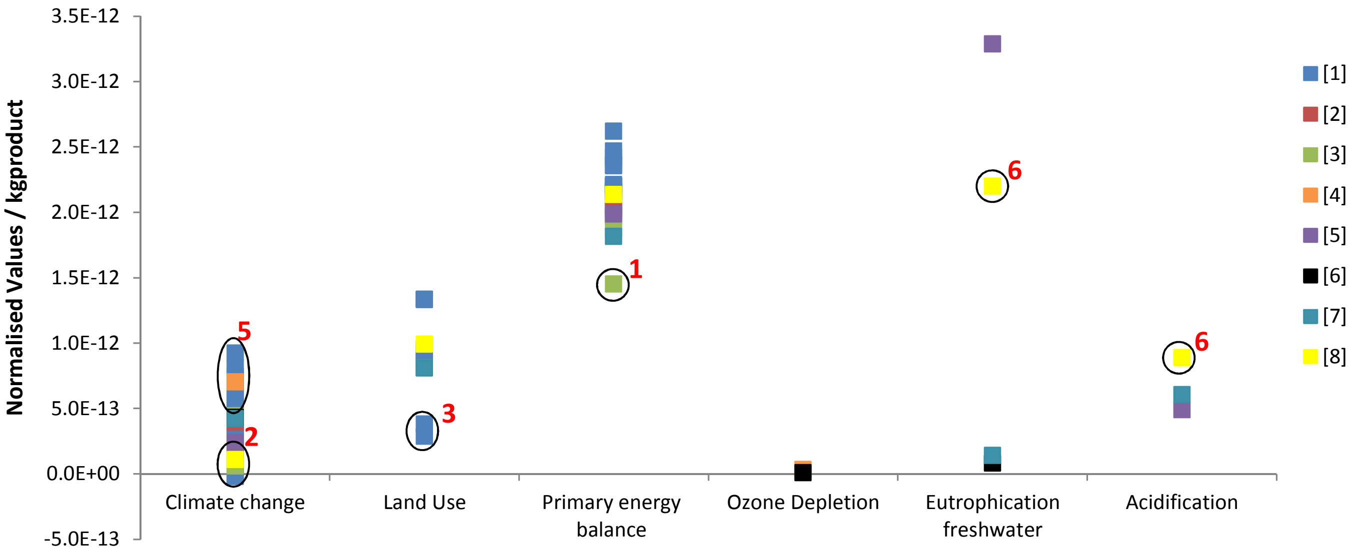

Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. Reference 3 presents a scenario where calcium sulphate is considered as co-product (used in land applications) and a credit was given to the PLA system due to the avoided impacts of calcium sulphate mining. This credit decreases the primary energy demand and the climate change impacts;
2. The lowest values found for climate change and non-renewable energy demand were obtained for the production of PLA from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [1] for the energy surplus generated from bagasse burn;
3. The land requirements for PLA production using corn stover are lower when compared with corn and sugar cane. This is due to the economic allocation applied [1], which assigns a lower value to corn stover than corn kernels;
4. The authors of reference [1] account for the burning of lignin-rich waste [obtained in the pretreatment (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. The highest values found for climate change impact were obtained from studies considering cradle to grave boundaries, which means that the use and end-of-life phases are environmentally significant;
6. Eutrophication and acidification impact values for PLA production from sugar cane are higher than the majority of the values found for corn.

REFERENCES / FURTHER INFORMATION

[1] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/
[2] Vink et al., 2003. Polym Degrad Stabil 80: 403–419.
[3] Vink et al., 2007. Industrial Biotechnology 3: 58-81.
[4] Hottle et al., 2013. Polym Degrad Stabil 98: 1898-1907.
[5] Gironi and Piemonte, 2011. Environ Prog & Sustainable Energy 30: 459-468.
[6] Madival et al., 2009. J Clean Prod 17: 1183–1194.
[7] Detzel, A., Krüger, M. Life Cycle Assessment of Polylactide (PLA) A comparison of food packaging made from NatureWorks® PLA and alternative materials, IFEU GmbH, Heidelberg, July 2006.
[8] Groot and Borén, 2010. The International J Life Cycle Assessment 15: 970-984.
[9] Benini et al., Normalisation method and data for Environmental Footprints, JRC Technical Report, Draft v.2014.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC