nature portfolio

https://doi.org/10.1038/s41578-021-00407-8

Supplementary information

Bioplastics for a circular economy

In the format provided by the authors and unedited

Supplementary Information for

Bioplastics for a circular economy

Jan-Georg Rosenboom[1,2,3], Robert Langer[1,2†] and Giovanni Traverso[2,3,4†]

[1]Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.
[2]Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA, USA.
[3]Division of Gastroenterology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA.
[4]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.
[†]e-mail: rlanger@mit.edu; cgt20@mit.edu

Table S1 | **Comparison of material properties of some commercially relevant synthetic fossil-based and bio-based polymers**

Polymer	T_m (°C)	T_g (°C)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)
Fossil-based and durable					
HDPE[1,2]	130	>–70	45	>1	640
LDPE[1,2]	110	–100	20	0.25	500
PP[2,3]	<175	–10	35	<17	>200
PS[4,2]	240	100	42	3.6	5
PET[1,5]	245	75	58	3.1	>300
PVC[4,6]	100	<115	58	2.8	5
Fossil-based and degradable					
PBAT[1]	120	–33	23	0.08	470
PBS[1,7,8]	115	–32	33	0.6	>170
PVA[9]	230	80	46	1.8	NA
PCL[1,10,11]	60	–60	23	0.4	600
Bio-based and durable					
PEF[12,5,13]	220	85	76	1.9	>100
bioPET	same as PET				
bioPE	same as PE				
Bio-based and degradable					
bioPBS	same as PBS				
PLA[1,2]	160	50	65	3.8	4
PGA[2,6]	225	40	>80	8.4	30
P3HB[14,3,15]	175	2.5	25	2.8	5
P4HB[16,2,17]	60	–51	>50	0.07	1,000

Degradable polymers describe those that contain readily hydrolysable aliphatic ester bonds in their backbone structure, and PVA whose degradation follows a diketone pathway. Durable polymers are those with a backbone that is typically more resistant to enzymatic and non-enzymatic hydrolysis, such as aromatic esters, amides and C–C bonds. Note that non-zero degradation may occur in any polymer. The listed material properties are taken from various references where available and, therefore, must be considered indications of typical values in common applications, but may vary depending on molecular weight, formulation with additives and processing. Some classes of copolymers, such as polyurethanes and polyanhydrides, as well as composite blends, have been excluded for space and complexity reasons. bioPET, bioPE and bioPBS are the drop-in bio-variants of PET, PE and PBS, respectively, and can be assumed to have the same materials properties as those of their fossil-derived analogues. [a]Units for gas permeation are ml/m^2/day/atm for gases and g/m^2/day for water vapour. HDPE, high-density polyethylene; LDPE, low-density polyethylene; P3HB, poly(3-hydroxybutyrate); P4HB, poly(4-hydroxybutyrate); PBAT, polybutylene adipate-*co*-terephthalate; PBS, polybutylene succinate; PCL, polycaprolactone; PEF, polyethylene furanoate; PET, polyethylene terephthalate; PGA, polyglycolic acid; PLA, polylactic acid; PP, polypropylene; PS, polystyrene; PVA, polyvinyl alcohol; PVC, polyvinylchloride; T_g, glass transition temperature; T_m, melting temperature.

Table S2 | **Large-volume producers of bioplastics**

Polymer	**Company**	**Location**	**Capacity (tonnes per year)**	**Year of operation**	**Comments and planned capacities (tonnes per year)**
PLA[1,6,18]	NatureWorks (PTT and Cargill)	USA	150,000	2002	>75,000 in Thailand by 2024
PLA[1,6,19]	Corbion and Total	Thailand	75,000	2019	>100,000 in France by 2024
PLA[20]	BBCA Group	China	40,000	2020	700,000 by 2023
PBS[21]	PTT MCC Biochem	Thailand and Japan	20,000	2017	Uses 50% bio-based succinic acid and 50% petro-based butanediol
PBS[21,22]	BASF and Corbion	Spain	10,000	2014	
PBS[23]	Hexing Chemical	China	10,000	2009	
PHA[14]	Tianjin GreenBio Materials	China	10,000	NA	
PHA[24]	Danimer Scientific	USA	9,000	2019	30,000 by 2022, 113,000 by 2024
PHAs[24]	RWDC Industries	Singapore and USA	5,000	2015	25,000 per year by 2023
P3HB-4HB[25]	CheilJedang	South Korea and USA	5,000	2021	Relaunch of Metabolix technology
PHAs[24]	Bio-On	Italy	1,000	NA	Bankrupt
PHBV[21,14]	Tianan	China	2,000	NA	Solvent-free process
PBAT[1,26]	BASF	Germany	74,000	1990	Fossil-based polymer
PBAT[26,27]	Jinhui Zhaolong High	China	20,000	NA	
bioPE[21,28]	Braskem “I’m Green”	Brazil	200,000	2010	260,000 by 2023
bioPP[29]	Neste and Borealis	Belgium	NA	NA	
bioPET[30]	Virent and Coca-Cola	USA	NA	2014	
bio-*para*-xylene for bioPET[31]	Gevo	USA	NA	NA	
bioPET[26,2]	Coca-Cola	USA	NA	NA	Made from bio-based ethylene glycol and fossil-derived terephthalic acid
PEF[21,32]	Avantium	Netherlands	NA	NA	5,000 t of FDCA per year by 2023
PEF[33]	Corbion	Netherlands	NA	NA	Fermentation process for FDCA
PEF[32,34]	SULZER	Switzerland	NA	NA	Ring-Opening Polymerization
Bio-Nylon-6,6[35]	Genomatica	USA	NA	NA	Bio-Caprolactam
Starch-based polymers[26]	Novamont	Italy	150,000	NA	85% Starch, the rest fossil-derived
Cellulose[36]	VTT	Finland	NA	NA	Films
Cellulose[37]	Stora Enso	Finland	NA	NA	Foams

NA, not available. P3HB, poly(3-hydroxybutyrate); P4HB, poly(4-hydroxybutyrate); PBAT, polybutylene adipate-*co*-terephthalate; PBS, polybutylene succinate; PE, polyethylene; PEF, polyethylene furanoate; PET, polyethylene terephthalate; PHA, polyhydroxyalkanoates; PHBH, poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate); PHBV, poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate); PLA, polylactic acid; PP, polypropylene.

References

1. Künkel, A. *et al.* Polymers, Biodegradable. in *Ullmann's Encyclopedia of Industrial Chemistry* 1–29 (2016).
2. Lamberti, F. M., Román-Ramírez, L. A. & Wood, J. Recycling of Bioplastics: routes and benefits. *J. Polym. Environ.* **28**, 2551–2571 (2020).
3. Harding, K. G., Dennis, J. S., von Blottnitz, H. & Harrison, S. T. L. Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis. *J. Biotechnol.* **130**, 57–66 (2007).
4. Chanda, M. & Roy, S. K. *Plastics Technology Handbook*. *Taylor & Francis* (2006).
5. Rosenboom, J.-G., Hohl, D. K., Fleckenstein, P., Storti, G. & Morbidelli, M. Bottle-grade Polyethylene Furanoate from Ring-Opening Polymerisation of Cyclic Oligomers. *Nat. Commun.* **9**, 2701 (2018).
6. Jem, K. J. & Tan, B. The development and challenges of poly(lactic acid) and poly(glycolic acid). *Adv. Ind. Eng. Polym. Res.* **3**, 60–70 (2020).
7. Siracusa, V., Lotti, N., Munari, A. & Dalla, M. Poly(butylene succinate) and poly(butylene succinate-co-adipate) for food packaging applications: Gas barrier properties after stressed treatments. *Polym. Degrad. Stab.* **119**, 35–45 (2015).
8. Mitsubishi Chemical Corporation. *Biodegradable Polymer BioPBS*. https://www.m-chemical.co.jp/en/products/departments/mcc/sustainable/product/1201025_7964.html
9. Ben Halima, N. Poly(vinyl alcohol): review of its promising applications and insights into biodegradation. *RSC Adv.* **6**, 39823–39832 (2016).
10. Labet, M. & Thielemans, W. Synthesis of polycaprolactone: a review. *Chem. Soc. Rev.* **38**, 3484–3504 (2009).
11. Ikada, Y. & Tsuji, H. Biodegradable polyesters for medical and ecological applications. *Macromol. Rapid Commun*. **21**, 117–132 (2000).
12. De Jong, E., Dam, M. A., Sipos, L. & Gruter, G. J. M. Furandicarboxylic acid (FDCA), A versatile building block for a very interesting class of polyesters. *ACS Symposium Series* (ed. Smith, P.) vol. 1105 1–13 (ACS, 2012).
13. Burgess, S. K., Karvan, O., Johnson, J. R., Kriegel, R. M. & Koros, W. J. Oxygen sorption and transport in amorphous poly (ethylene furanoate). *Polymer (Guildf).* **55**, 4748–4756 (2014).
14. Plackett, D. & Siró, I. Polyhydroxyalkanoates (PHAs) for food packaging. in *Multifunctional and Nanoreinforced Polymers for Food Packaging* 498–526 (Elsevier, 2011).
15. Meereboer, K. W., Misra, M. & Mohanty, A. K. Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. *Green Chem.* **22**, 5519–5558 (2020).
16. Utsunomia, C., Ren, Q. & Zinn, M. Poly(4-Hydroxybutyrate): Current State and Perspectives. *Front. Bioeng. Biotechnol.* **8**, 257 (2020).
17. Nakajima, H., Dijkstra, P. & Loos, K. The recent developments in biobased polymers toward general and engineering applications: Polymers that are upgraded from biodegradable polymers, analogous to petroleum-derived polymers, and newly developed. *Polymers (Basel).* **9**, 523 (2017).
18. Business Wire. *NatureWorks Announces Key Milestones for Global Manufacturing Expansion with New 75kTa Facility for Producing Ingeo Biopolymer in Thailand*. https://www.natureworksllc.com/News-and-Events/Press-Releases/2021/2021-06-02-Thailand-Ingeo-PLA-plant-announcement (2021).
19. Total Corbion PLA. *Total Corbion PLA enters engineering stage for new 100 kTpa PLA plant in Grandpuits, France*. https://www.total-corbion.com/news/total-corbion-pla-enters-engineering-stage-for-new-100-ktpa-pla-plant-in-grandpuits-france/ (2021).
20. Shuhei Yamada, Y. F. China aims to go as big in bioplastics as it did in solar panels. *Nikkei Asia* https://asia.nikkei.com/Spotlight/Environment/China-aims-to-go-as-big-in-bioplastics-as-it-did-in-solar-panels (2021).
21. Chen, J. Global Markets and Technologies for Bioplastics. *bcc Research Report*

Code: PLS050E 1–231 (2019).
22. BASF. *Succinity produces first commercial quantities of biobased succinic acid*. https://www.basf.com/fi/en/media/news-releases/2014/03/p-14-0303-ci.html (2014).
23. Xu, J. & Guo, B. Poly(butylene succinate) and its copolymers: research , development and industrialization. *Biotechnol. J.* **5**, 1149–1163 (2010).
24. Tullo, A. H. Will the biodegradable plastic PHA finally deliver? *Chem. Eng. News* https://cen.acs.org/business/biobased-chemicals/biodegradable-plastic-PHA-finally-deliver/99/i22 (2021).
25. European Bioplastics. *Member portrait: CJ Europe*. https://www.european-bioplastics.org/member-portrait-cj-europe/ (2021).
26. Aeschelmann, F. & Carus, M. Industry Report - Biobased Building Blocks and Polymers in the World: Capacities, Production, and Applications–Status Quo and Trends Towards 2020. 154–159 (2015).
27. Biodegradable Products Institute. *Jinhui Zhaolong High Technology Co., Ltd*. https://products.bpiworld.org/companies/jinhui-zhaolong-high-technology-co-ltd
28. Braskem. *Braskem invests US$61 million to increase biopolymer production*. https://www.braskem.com.br/usa/news-detail/braskem-invests-us61-million-to-increase-biopolymer-production (2021).
29. NESTE. *Borealis producing certified renewable polypropylene from Neste's renewable propane at own facilities in Belgium*. https://www.neste.com/releases-and-news/circular-economy/borealis-producing-certified-renewable-polypropylene-nestes-renewable-propane-own-facilities-belgium (2020).
30. Virent. Virent BioFormPX® paraxylene used for world's first pet plastic bottle made entirely from plant-based material. https://www.virent.com/news/virent-bioformpx-paraxylene-used-for-worlds-first-pet-plastic-bottle-made-entirely-from-plant-based-material/ (2015).
31. Bioplastics magazine. *Gevo supplies renewable para-xylene to Toray for production of bio-PET*. https://www.bioplasticsmagazine.com/en/news/meldungen/Gevo-supplies-px.php (2014).
32. Loos, K. *et al.* A Perspective on PEF Synthesis, Properties, and End-Life. *Front. Chem.* **8**, 585 (2020).
33. Corbion. *The future of plastics is biobased*. http://www.corbion.com/bioplastics/fdca.
34. Sulzer. *Shaping the future of polyesters*. https://www.sulzer.com/en/shared/applications/polyethylene-furanote-pef.
35. Schilling, C. & Weiss, S. A Roadmap for Industry to Harness Biotechnology for a More Circular Economy **60**, 9–11 (2021).
36. VTT. *Advances in cellulose-based food packaging material move to testing phase of industrial production*. https://www.vttresearch.com/en/news-and-ideas/advances-cellulose-based-food-packaging-material-move-testing-phase-industrial (2021).
37. Stora Enso. *A world of possibilities with a bio-based foam for packaging*. https://www.storaenso.com/en/products/bio-based-materials/cellulose-foam.