Bioplastics

(Bio-based and Compostable Plastics)

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Bioplastics landscape

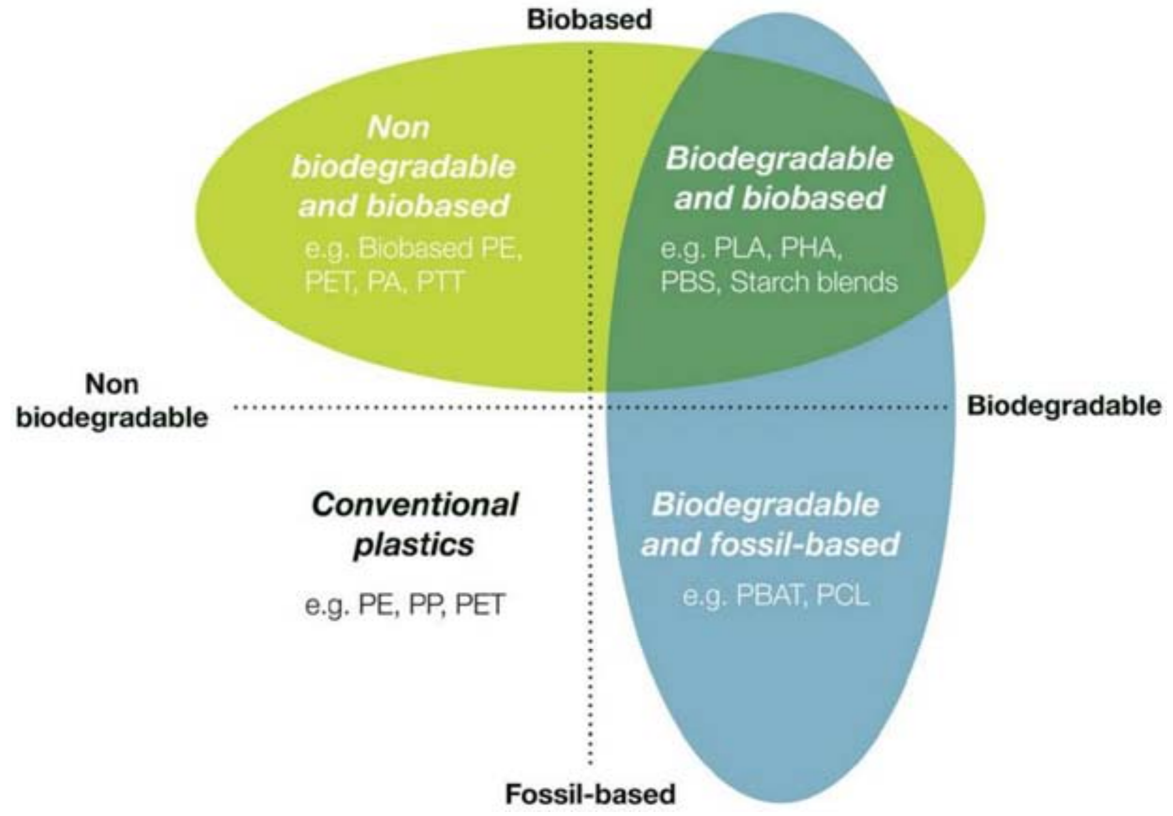
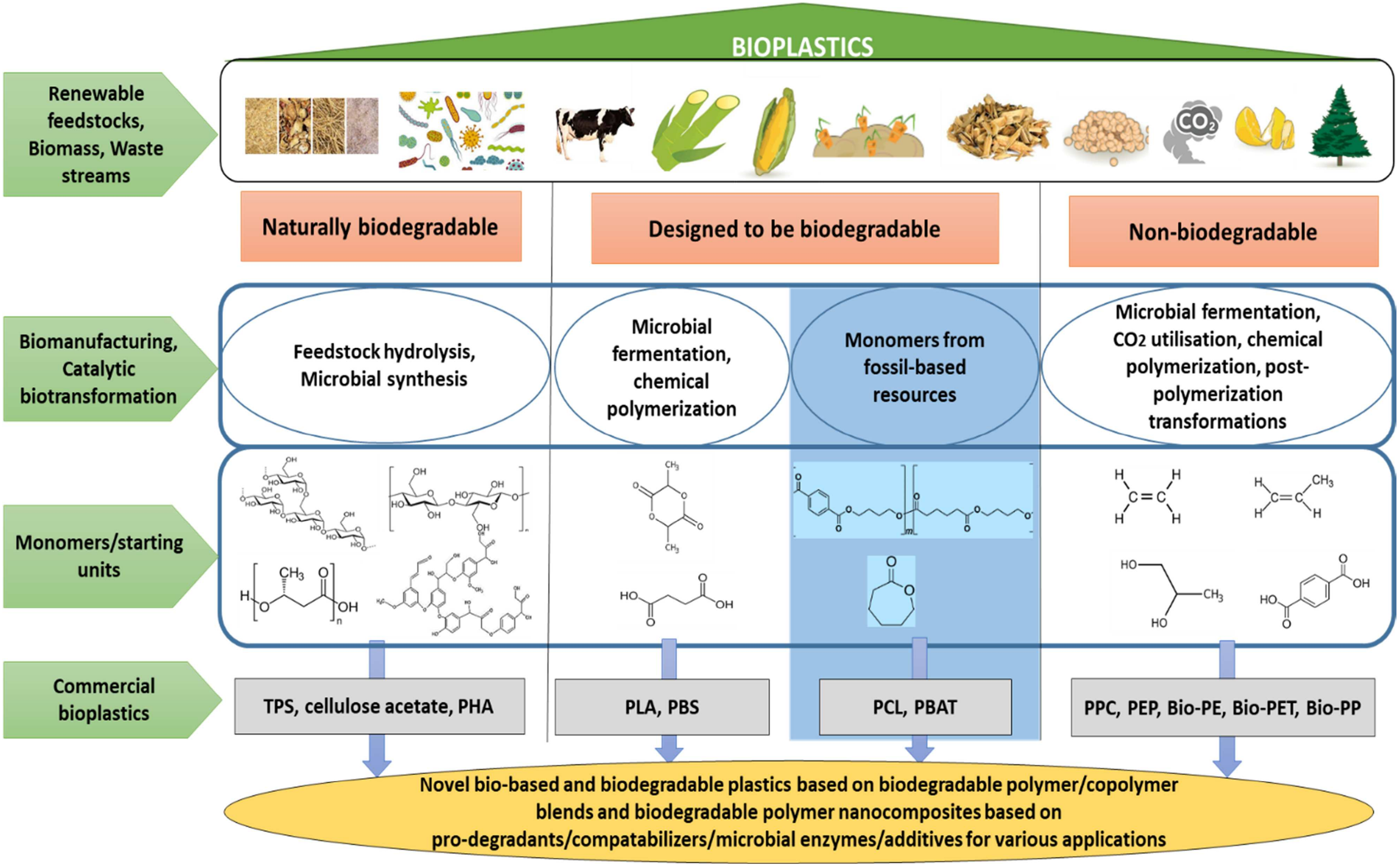


Figure 1. *Understanding the three different categories of bioplastics [23].*

PE	Polyethylene
PET	Polyethylene terephthalate
PA	Polyamine (Nylon)
PTT	Polytrimethylene terephthalate
PLA	Polylactic acid
PHA	Polyhydroxyalkanoates
PBS	Polybutylene succinate (polytetramethylene succinate)
PBAT	Polybutylene adipate terephthalate
PP	Polypropylene
PEF	Poly (Ethylene 2, 5-Furandicarboxylate)
PCL	Polycaprolactone
TPS	Thermoplastic Starch

Shamsuddin, I.M., Jafar, J.A., Shawai, A.S.A., Yusuf, S., Lateefah, M. and Aminu, I., 2017. Bioplastics as better alternative to petroplastics and their role in national sustainability: a review. *Advances in Bioscience and Bioengineering*, *5*(4), p.63.



Rameshkumar, S., Shaiju, P., O'Connor, K. E., & Babu P, R. (2019). *Bio-based and biodegradable polymers - State-of-the-art, Challenges and Emerging Trends. Current Opinion in Green and Sustainable Chemistry.* doi:10.1016/j.cogsc.2019.12.005

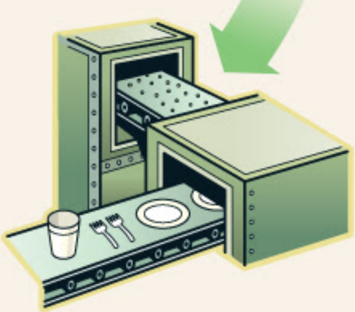
The Life Cycle of Bioplastics

Some bioplastics decompose in a fairly short period of time, and the full life cycle of such products is shown here. Other bioplastics aren't biodegradable. But even in those cases, the use of plant-based raw materials means that pollution is being removed from the atmosphere while the plants grow, giving bioplastics a green appeal.

Raw Materials
The process typically starts with growing plants such as sugar cane, corn and potatoes that are high in starches, the raw materials that replace petroleum products in bioplastics.

Extraction
The plant materials are harvested and processed to extract their starches.

Refining
The starches are processed further in bio-refineries through the use of special enzymes or fermentation (much as biofuels are made) to produce the chemical compounds that react to make plastics. The compounds can be refined to fit the specifications manufacturers need for different products.



Manufacturing
Bioplastics manufacturers use pellets or granules of the compounds to make utensils, plates, cup linings, carpeting and other products.

Disposal
When disposing of a bioplastic product that is fully biodegradable, consumers can place it in an organic-waste collection bin.

Compost and Renewal
The organic waste will compost and return to the earth as mulch to help new crops grow, completing the cycle.

Sources: CTC Clean Tech Consulting GmbH; WSJ reporting

Range of lifecycles of bioplastics in a circular economy

IC- Industrial composting
HC- Home composting
MR- Mechanical Recycling
AD-Anaerobic Digestion
CR-Chemical/catalytic Recycling
ED- Enzymatic depolymerisation

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Industrial Composting vs Home Composting

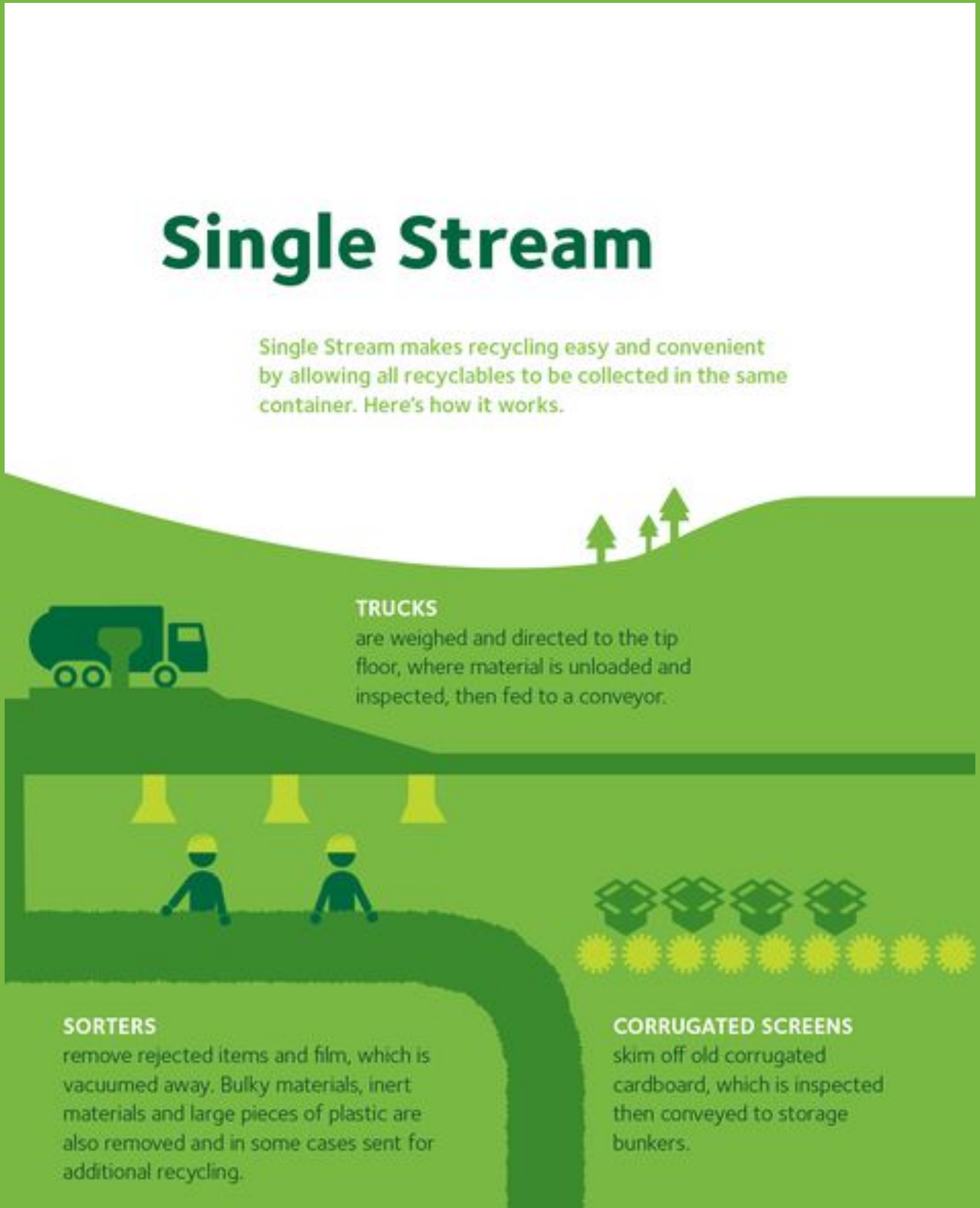
	ANAEROBIC BACTERIA, NO FUNGI			AEROBIC BACTERIA AND FUNGI
50 – 60 °C	Chemical pulp Starch PLA Starch/PLA PHA	THERMOPHILIC DIGESTION	INDUSTRIAL COMPOSTING	Chemical pulp Mechanical pulp Starch PLA Starch/PCL PHA PBAT
≤ 35 °C	Chemical pulp Starch Starch/PCL PHA	MESOPHILIC DIGESTION	HOME COMPOSTING	Chemical pulp Mechanical pulp Starch Starch/PCL PHA PBAT

cedar-grove.com/accepted-commercial-items

- Commercial composting can decompose meats, oils, and compostable plastics due to the higher heat and better aeration of the composting piles

Rujnić-Sokele, M. and Pilipović, A., 2017. Challenges and opportunities of biodegradable plastics: A mini review. *Waste Management & Research*, *35*(2), pp.132-140.

Recycling



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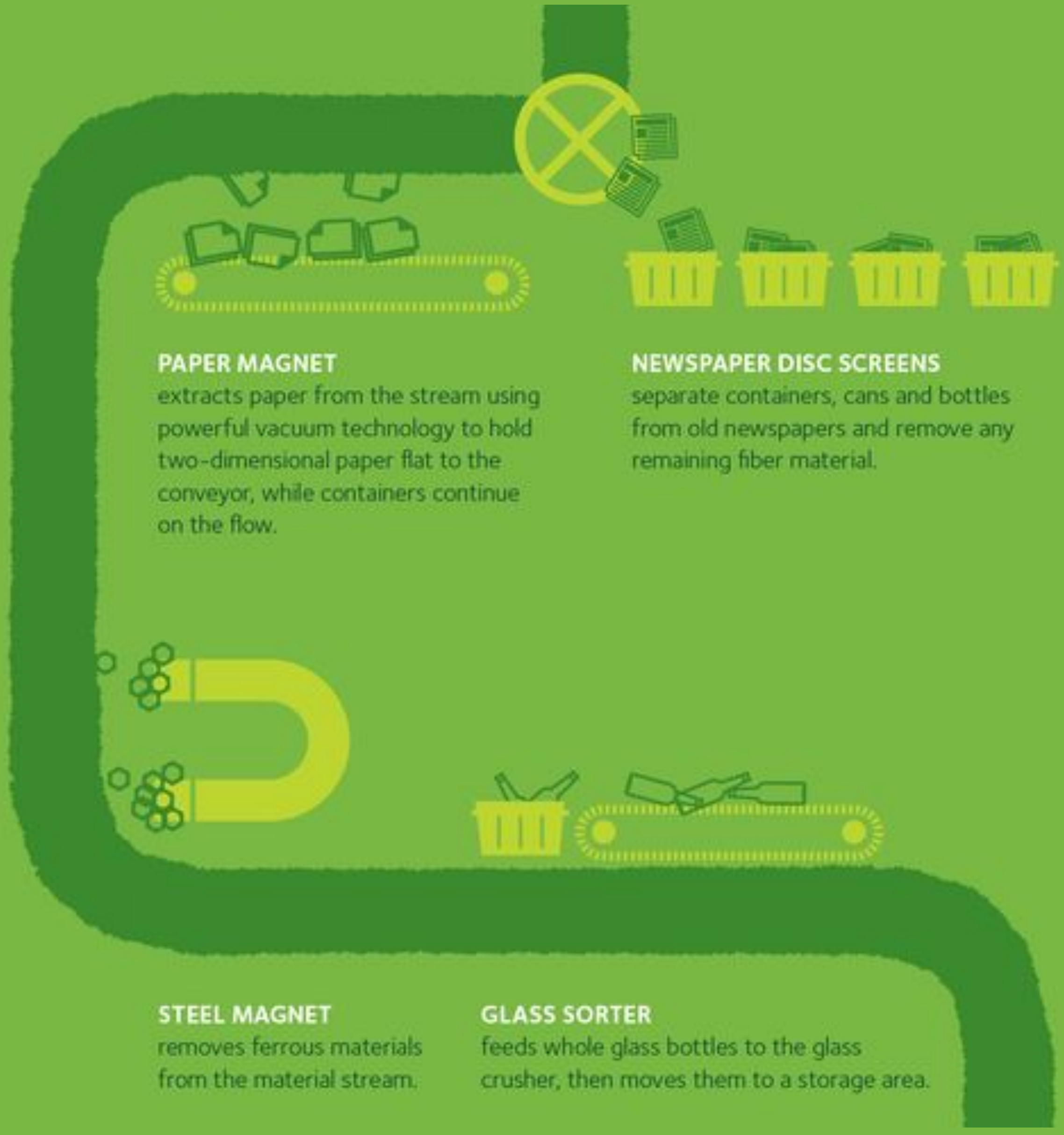
Recycling



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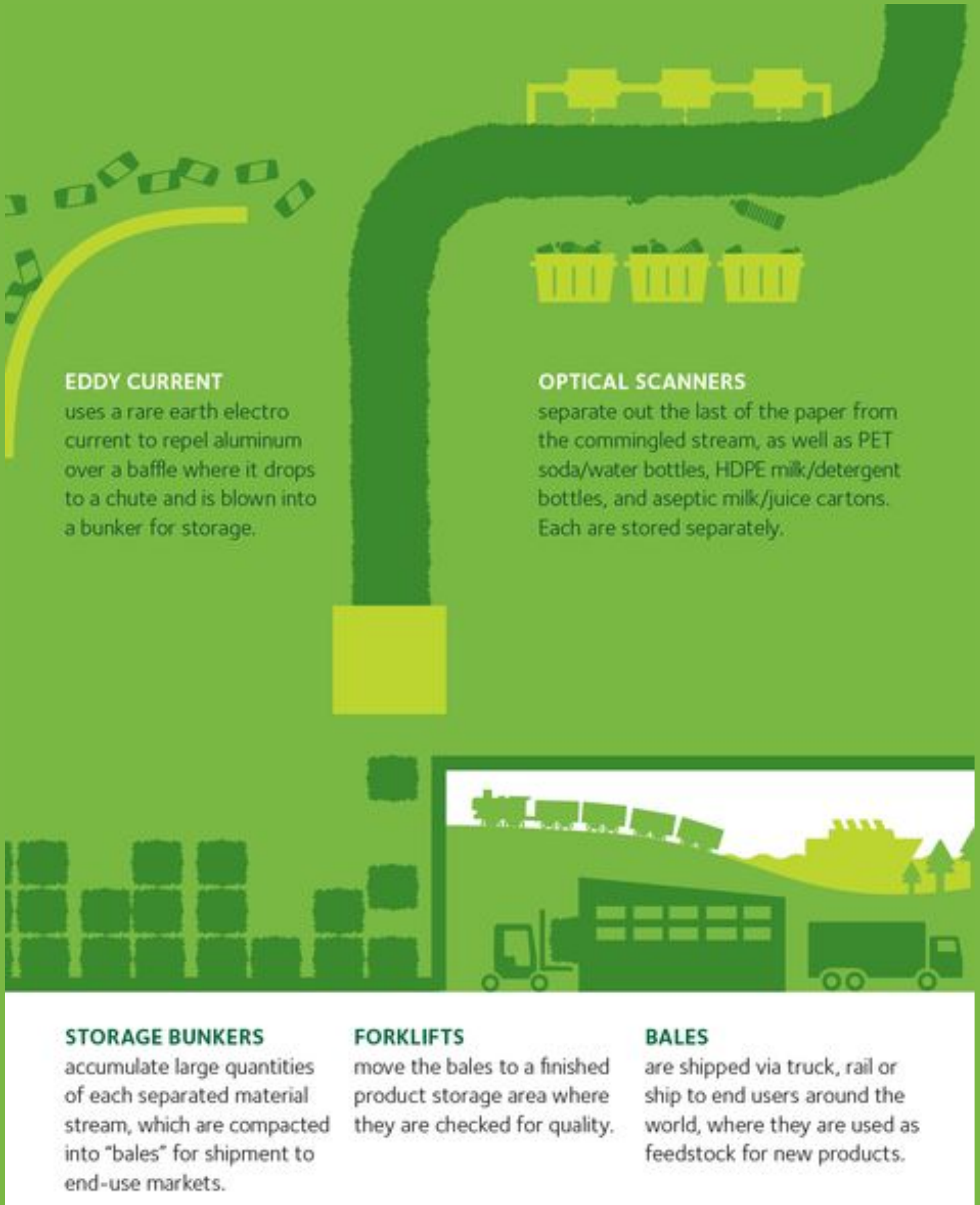

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General distribution and applications of plastics

Siracusa, V. and Blanco, I., 2020. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly (ethylene terephthalate)(Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers*, *12*(8), p.1641.

Biodegradable polymers Production			
Polymer Name	**Source/Feedstock**	**capacity (Kt/Year)**	**Sustainable end- of-life options**
TPS, Cellulose, Cellulose acetate, Starch blends	Biomass, agro- residues, lignocellulosic derivatives	384	HC, IC, AD
PLA & PLA blends	Lactic acid from dairy whey, corn starch or organic residues	225	IC, MR, CR
PHA, PHB, PHO	Volatile fatty acids, glucose/glycerol from fermentation of municipal solid waste or any carbon feedstocks	30	HC, IC, AD, CR
PCL	Chiral hydroxy acids, lactones	--	HC, IC, CR
PBS	Succinic acid, 1,4- butanediol	97	CR, ED
PBAT & PBAT blends	Terephthalic acid, adipic acid hydroxymethyl furfurals (HMFs), butanediol	152	IC, CR
AD-Anaerobic Digestion; MR- Mechanical Recycling; CR-Chemical/catalytic Recycling; ED- Enzymatic depolymerisation; IC- Industrial composting HC- Home composting			

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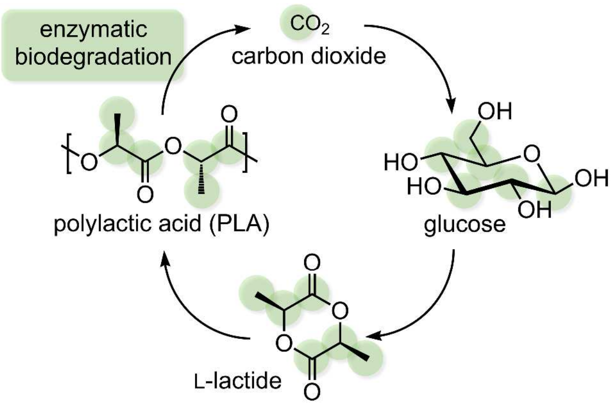
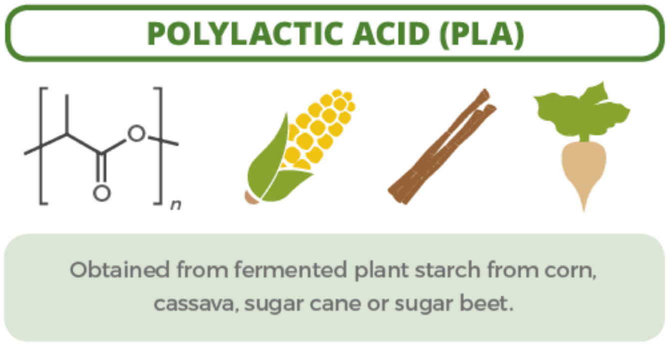
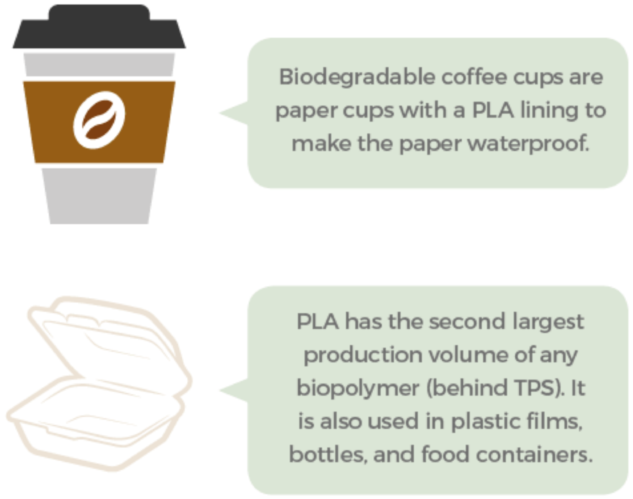
PLA & PLA blends

PLA is derived in a two step process that starts with fermenting the dextrose derived from a simple hydrolysis of corn starch. The product of the dextrose fermentation, lactic acid, is the basic building block of the Ingeo polylactide family of plastics. Lactic acid is further treated to create an intermediary monomer product called lactide, which is then polymerized through a process called ring opening polymerization to form PLA.



Scheme 1 The full lifecycle of polylactic acid (PLA) generally relies upon enzymatic biodegradation.

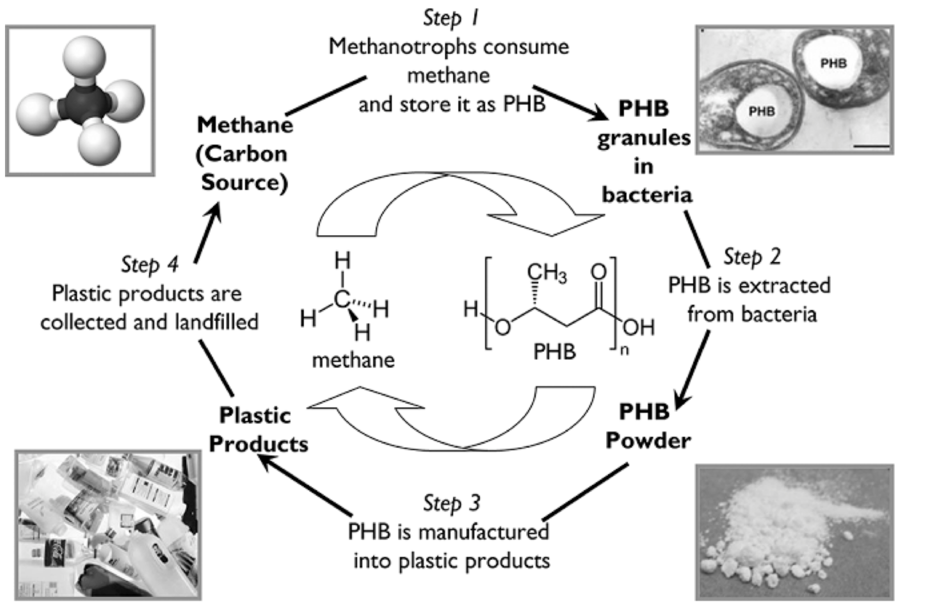




Marine-Degradable Polylactic Acid, Ryan T. Martin, Ludmila P. Camargo and Stephen A. Miller Green Chemistry, 2012, 00, 1-3

PHA, PHB, PHO

Corn sugars are fed into commercial fermentation systems where a proprietary strain of microbes digest the sugar and produce Polyhydroxyalkanoates, or PHA. PHA is an intracellular byproduct of the bacteria, meaning the bacteria actually create the plastic within their cells. The PHA is then harvested through the destruction of the bacteria and is separated from the microbial cell matter and formulated into Mirel resin.



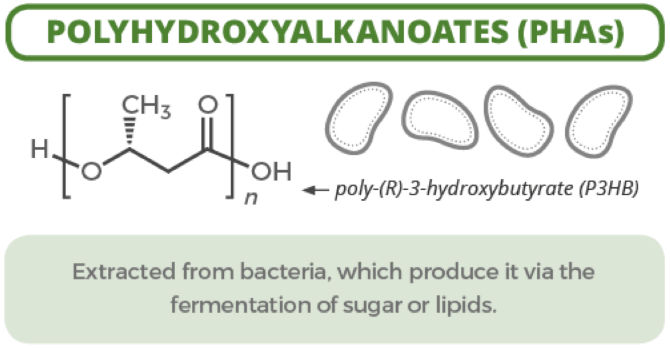
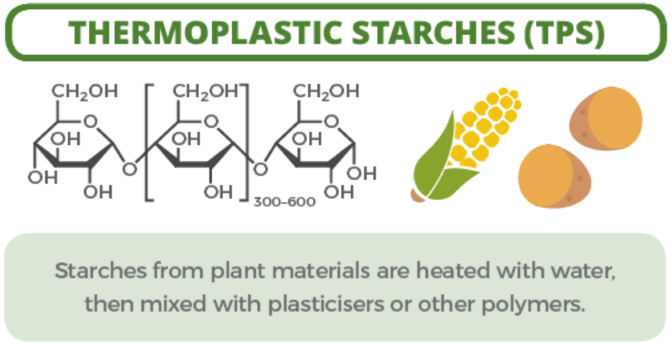


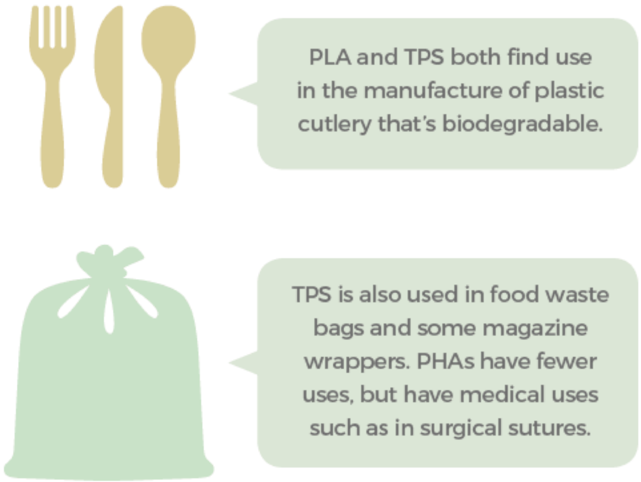
FIGURE 6. EXAMPLES OF MIREL/PHA PRODUCTS: BIOTUF BAGS, TARGET GIFT CARDS, SOILWRAP CONTAINER

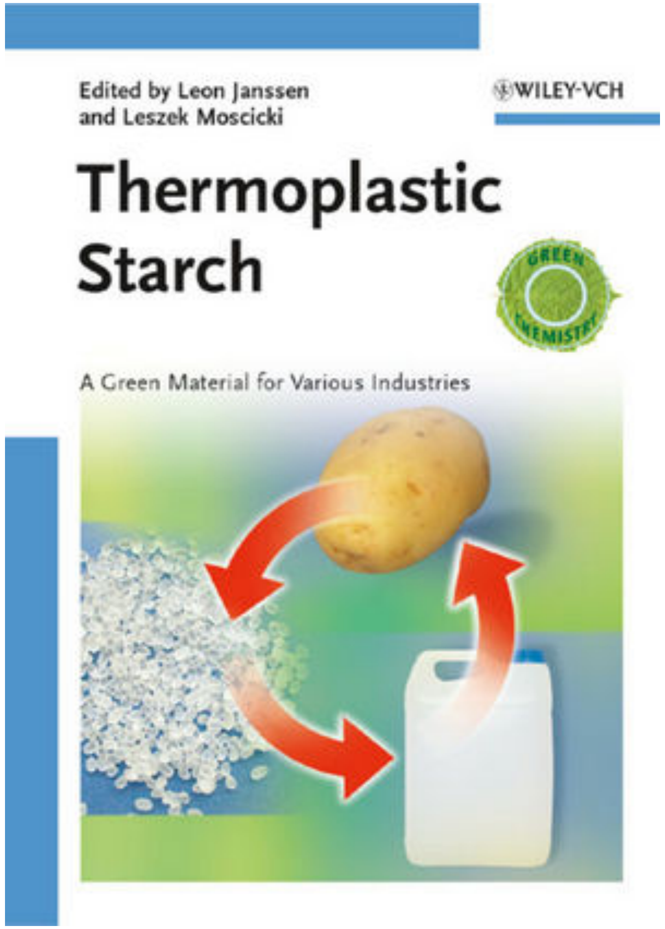
Compostable Plastics 101 California Organics Recycling Council 2011

TPS, Cellulose, Cellulose acetate, Starch blends

Much like PLA, or PHA, thermoplastic begins its life as starch. But instead of fermenting the starch, thermoplastics take advantage of starch plastic like polymer nature. The starch is first heated to destroy, or open up its inherently weak polymer structure. Then the starch is blended with complexing agents which are other polymers that reform with the starch creating a stronger biobased plastic.







Bio-based and non-biodegradable polymers			
Polymer Name	**Source/Feedstock**	**capacity (Kt/Year)**	**Sustainable end- of-life options**
Bio-PE	Bioethanol from sugarcane	200	MR
Bio-PET	Furan dicarboxylic 560 acid from HMF's	560	MR, CR, ED
Bio-PTT	1, 3-propanediol 45	45	MR, CR
Bio-PEF	HMF's	--	ED
Bio-PP	Isobutanol	--	MR
Bio-PA	Volatile fatty acids, HMF's	--	MR, CR
Bio- polycarbonates	Bioethanol/dialkyl - carbonate/epoxides and carbon-dioxide	--	CR
AD-Anaerobic Digestion; MR- Mechanical Recycling; CR-Chemical/catalytic Recycling; ED- Enzymatic depolymerisation; IC- Industrial composting HC- Home composting			

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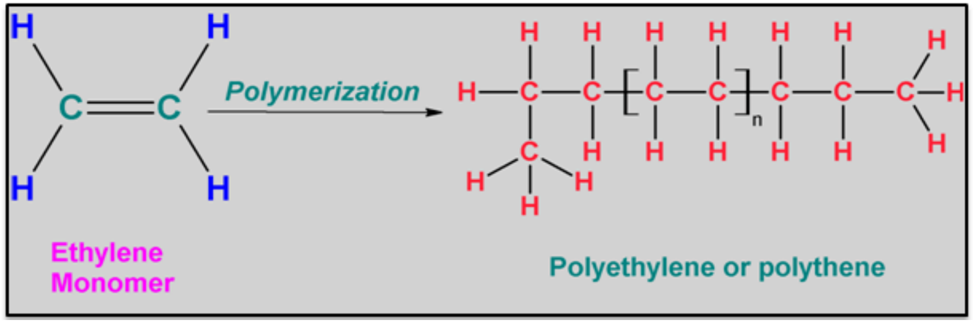
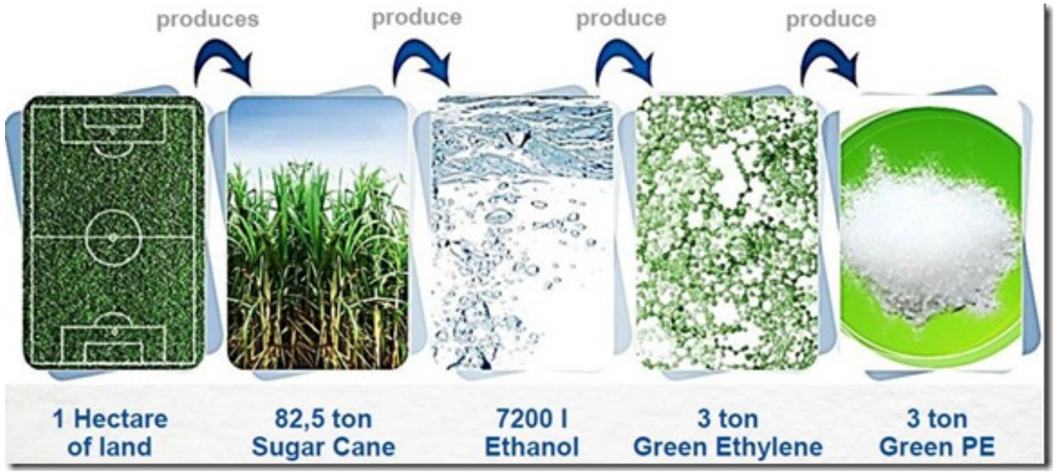
Bio-Polyethene





Bio-Polyethene is considered a "Drop in replacement" for petroleum based PE and can be recycled, but not composted.

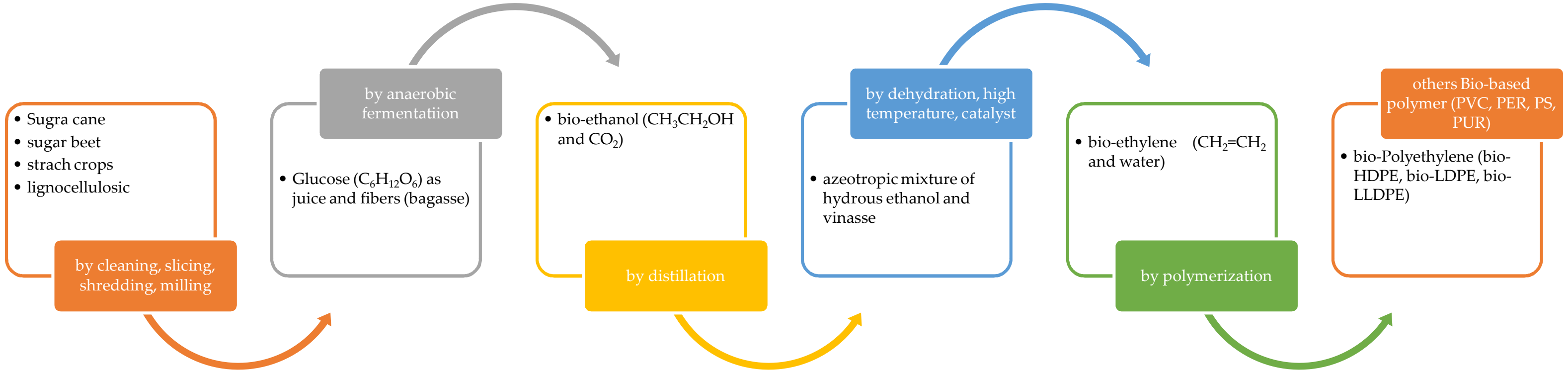
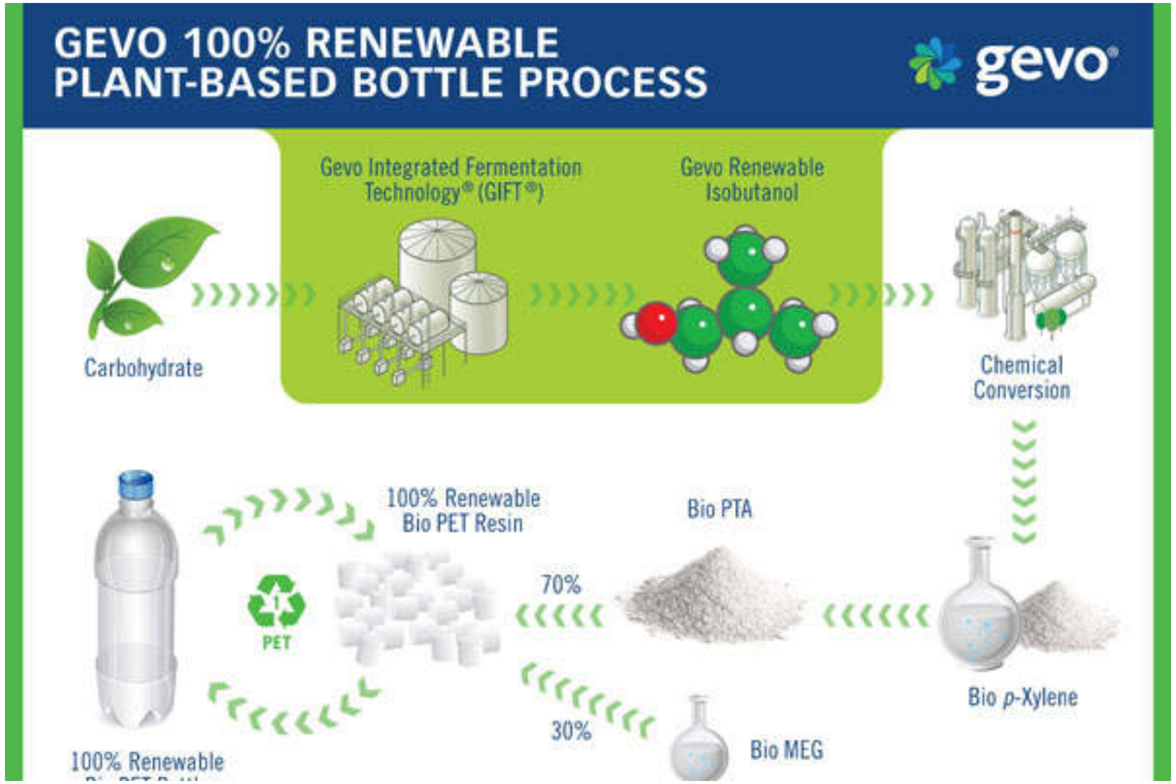


Figure 6. General scheme for Bio-PE production.

Siracusa, V. and Blanco, I., 2020. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly (ethylene terephthalate)(Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers*, *12*(8), p.1641.

BIO-PET

- Coca-Cola launched PlantBottle™, a fully-recyclable polyethylene terephthalate (PET) bottle made with 100% plant-based material, in June 2015,



Not biodegradable or compostable, recyclable .

https://www.packaging-gateway.com/projects/coca-cola-plant-based-bottle/ Accessed 02Oct2020

Bio-Polypropylene

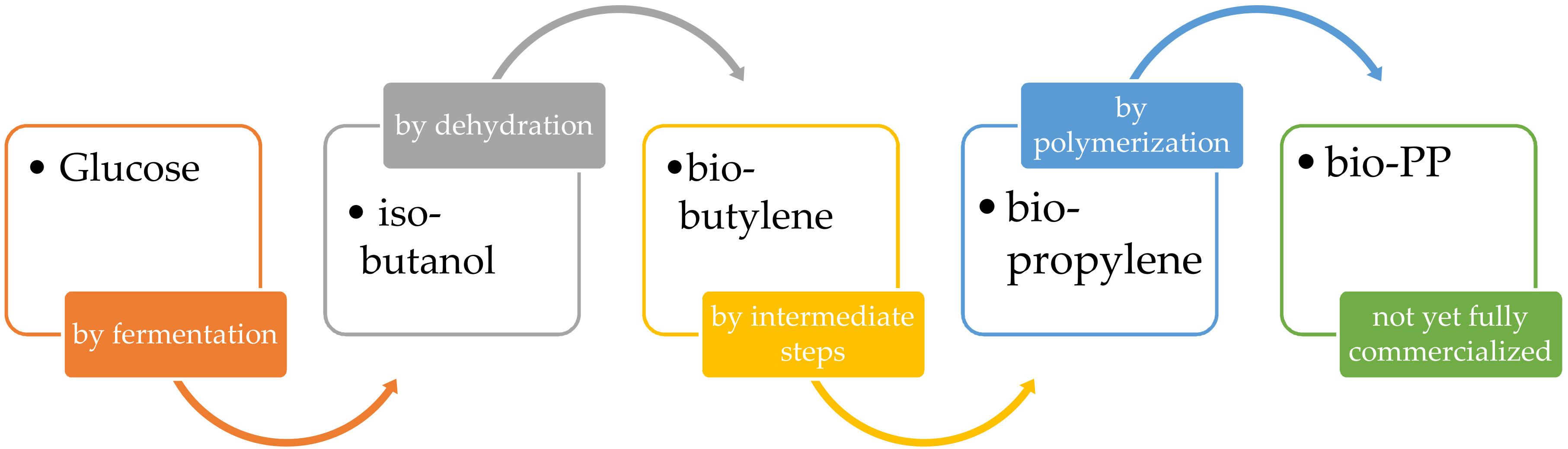


Figure 8. General scheme for Bio-PP.

Polypropylene is often used to make more durable goods, this would lead to more carbon sequestration. PP is also highly recyclable.

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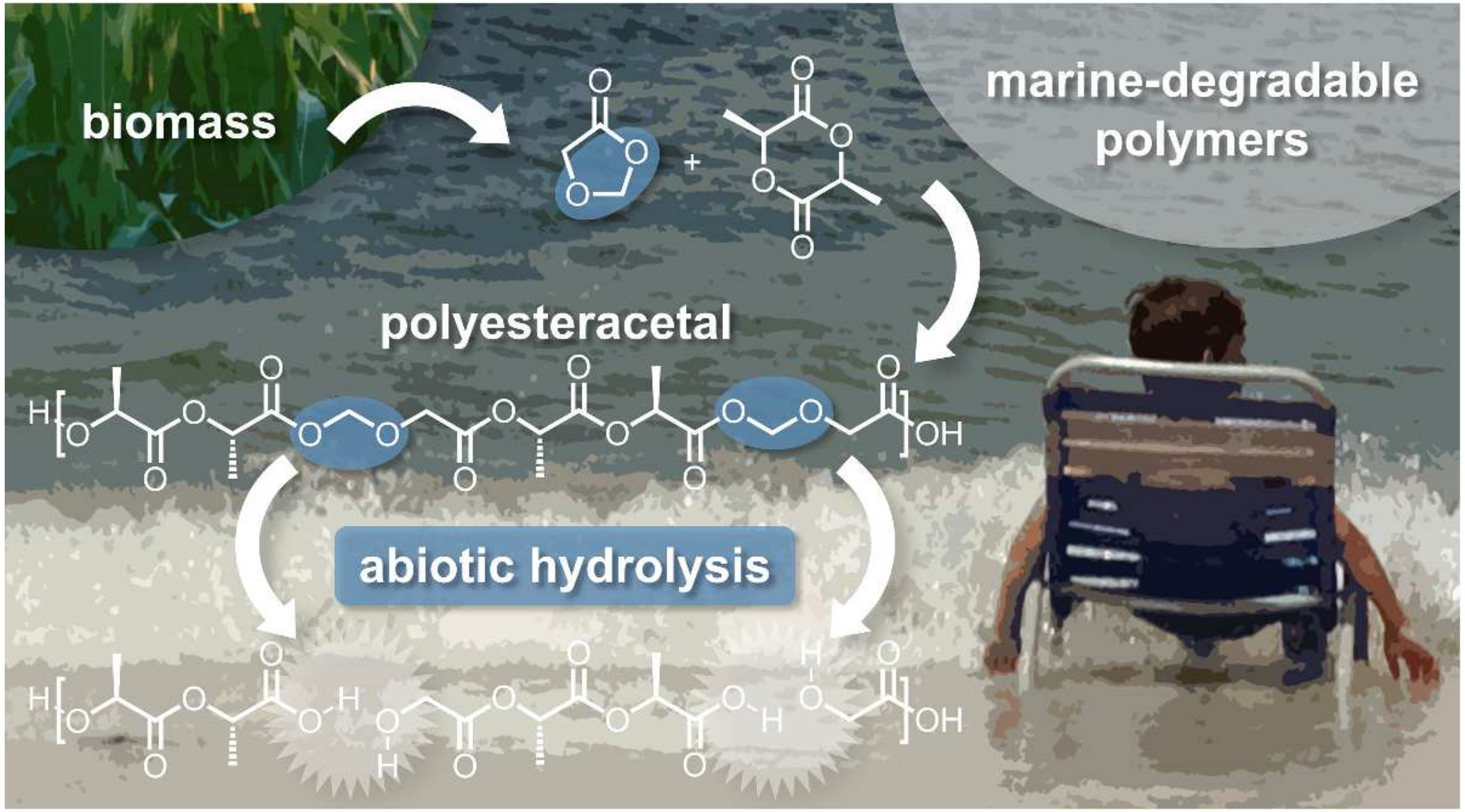
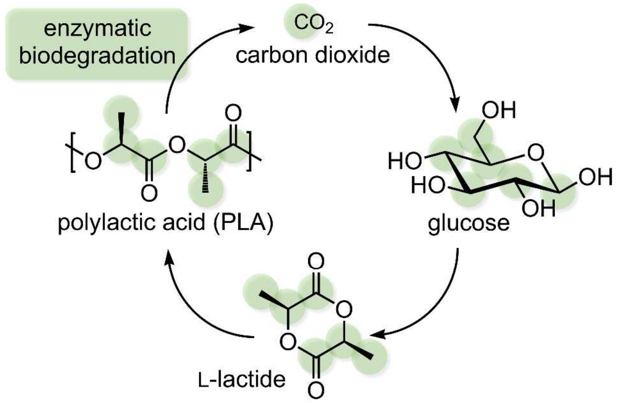
Marine Degradable Plastics



Marine-Degradable Polylactic Acid, Ryan T. Martin, Ludmila P. Camargo and Stephen A. Miller Green Chemistry, 2012, 00, 1-3

Marine Degradable Plastics



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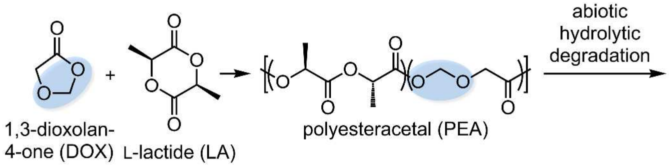


Scheme 3 Copolymerization strategy for synthesizing the polyesteracetal (PEA) copoly(lactide/1,3-dioxolan-4-one).

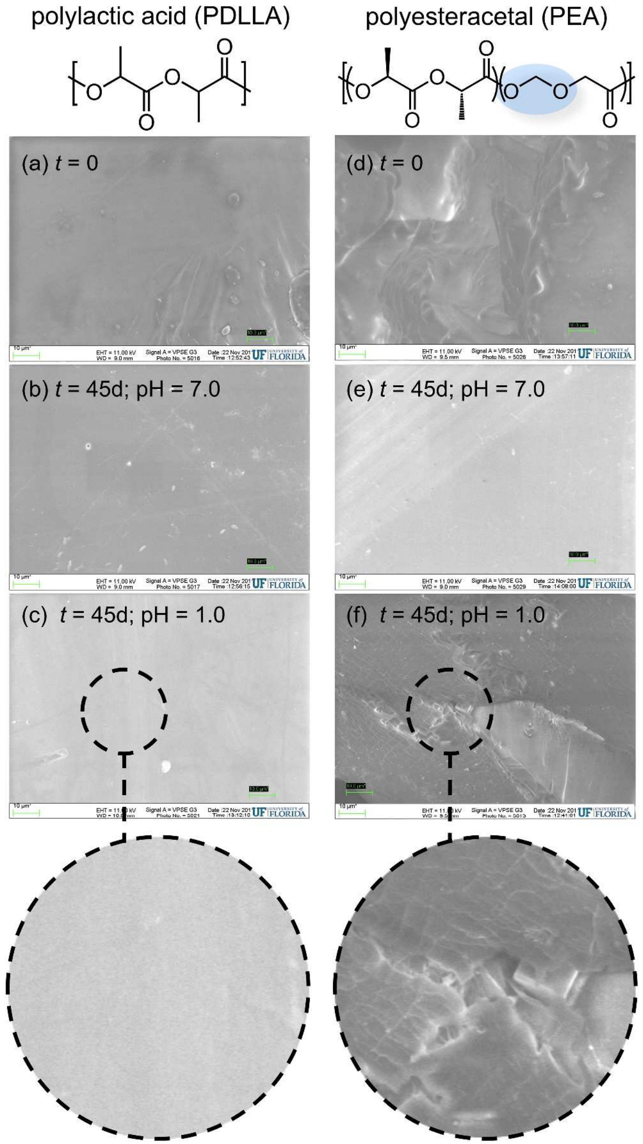


Figure 3 Under various aqueous conditions, surface erosion over 45 days is insignificant for poly(DL-lactide) (PDLLA) but is quite conspicuous for the polyesteracetal (4% DOX) when pH =1.

Marine-Degradable Polylactic Acid, Ryan T. Martin, Ludmila P. Camargo and Stephen A. Miller Green Chemistry, 2012, 00, 1-3

Plastic Precursors from Algae

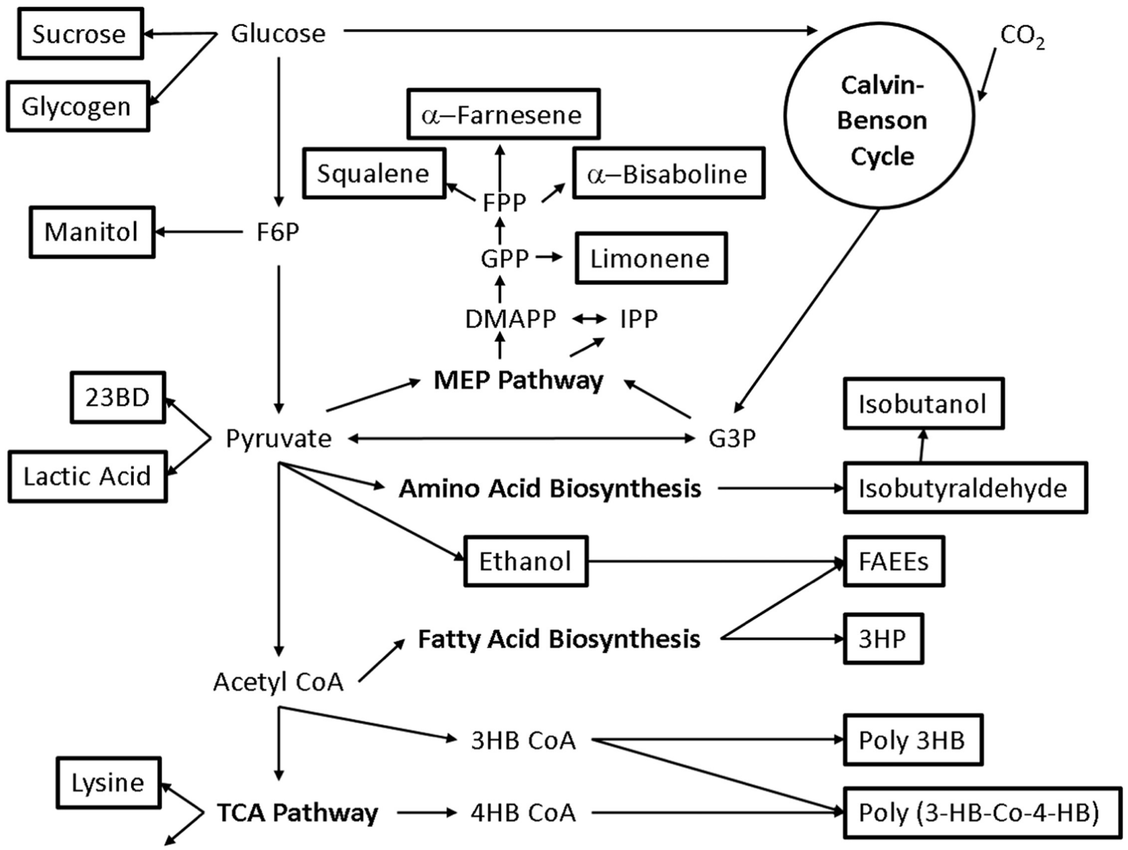


Fig. 1. Outline of metabolism and metabolic engineering in cyanobacteria. Boxed chemicals are discussed in this review. Abbreviations: 23BD, 2,3-butanediol; 3HB, 3-hydroxybutyrate; 4HB, 4-hydroxybutyrate; DMAPP, dimethylallyl pyrophosphate; F6P, fructose-6-phosphate; FAEE, fatty acid ethyl ester; FPP, farnesyl pyrophosphate; GPP, geranyl pyrophosphate; G3P, glyceraldehyde-3-phosphate; IPP, isopentenyl pyrophosphate; MEP, methylerythritol 4-phosphate; TCA, tricarboxylic acid.

Table 2
Cyanobacterial chemical production discussed in this review.

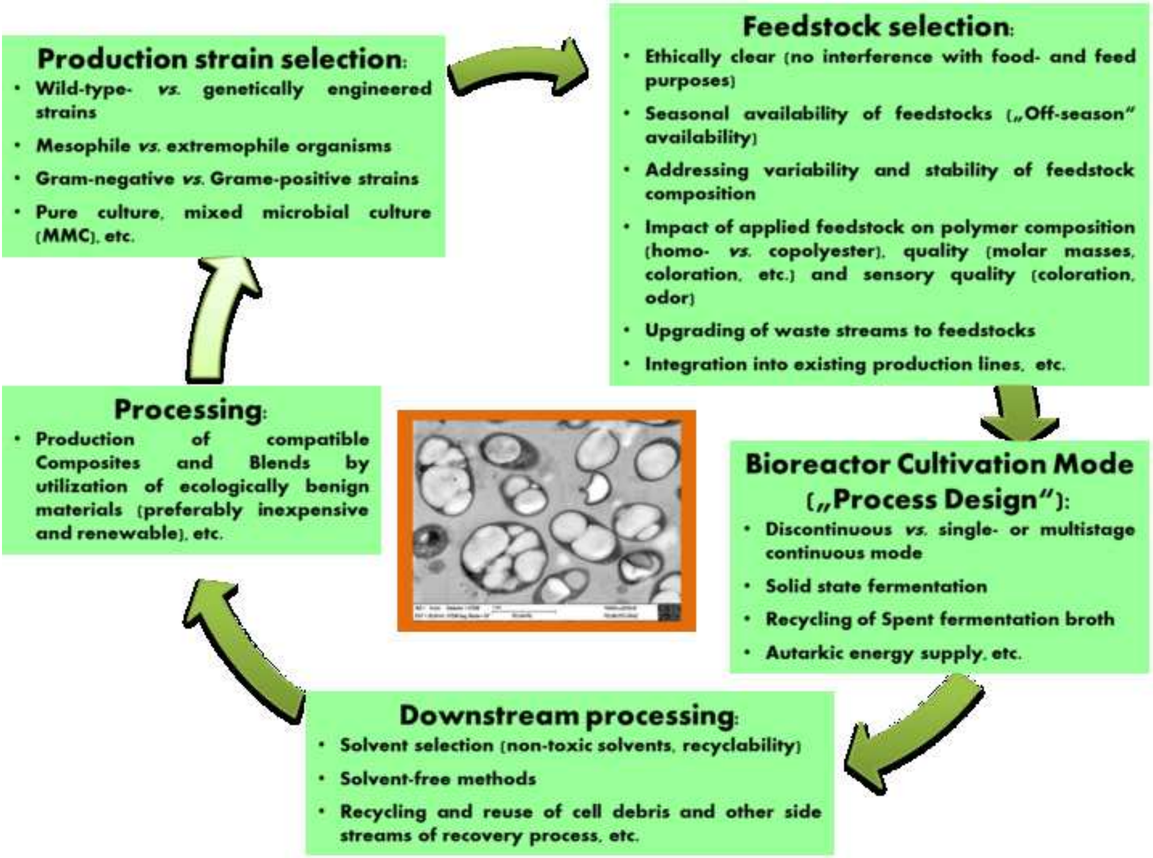
Strain	Compound	Titer (g/L)	References
2973	sucrose	3.3	Song et al., 2016
6803	3-hydroxypropionic acid	0.8	Wang et al., 2016b
	ethanol	5.5	Gao et al., 2012
	isobutanol	0.6	Miao et al., 2017
	lactic acid	0.8	Angermayr et al., 2014
	limonene	0.007	Lin et al., 2017
7002	2,3-butanediol	1.6	Nozzi et al., 2017
	alpha bisabolene	0.0006	Davies et al., 2014
	fatty acids	0.1	Ruffing, 2014
	glycogen	1.8	Aikawa et al., 2014
		3.0	
		3.5	
	limonene	0.004	Davies et al., 2014
	lysine	0.4	Korosh et al., 2017
	mannitol	1.1	Jacobsen and Frigaard, 2014
	poly-3-hydroxybutyrate	0.05	Zhang et al., 2015
7942	2,3-butanediol	3.0[a]	McEwen et al., 2016
		5.7[b]	Kanno et al., 2017
		12.6[a]	
	alpha-farnesene	0.005	Lee et al., 2017b
	ethanol	0.07	Deng and Coleman, 1999
	fatty acid ethyl esters	0.01	Lee et al., 2017a
	isobutyraldehyde	1.1	Atsumi et al., 2009
	isoprene	1.3	Gao et al., 2016
	limonene	0.005	Wang et al., 2016a
	squalene	0.05	Choi et al., 2017
	succinate	0.4	Lan and Wei, 2016
		7.3	Li et al., 2016b
	sucrose	2.6	Ducat et al. 2012
		0.8	Weiss et al., 2017

[a] Photomixotrophic production under continuous lighting.
[b] Photomixotrophic production under diurnal lighting.

*Synechocystis*sp. PCC 6803, *Synechococcus elongatus* PCC 7942, *Synechococcus*sp. PCC 7002, *Synechococcus elongatus*UTEX 2973

Carroll, A.L., Case, A.E., Zhang, A. and Atsumi, S., 2018. Metabolic engineering tools in model cyanobacteria. *Metabolic engineering*, *50*, pp.47-56.

Plastic Precursors from Algae



Schematic illustration of factors impacting sustainability of PHA production

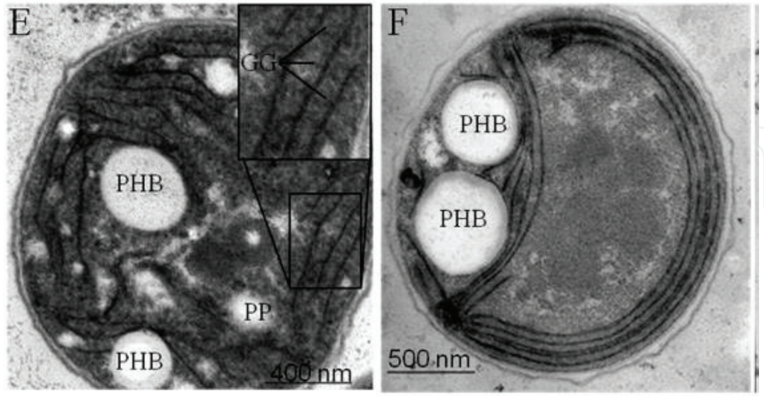


Figure 1.
PHB granules in cyanobacteria. Left: Wild type. Right: Mutant (reproduced with permission from [22]).

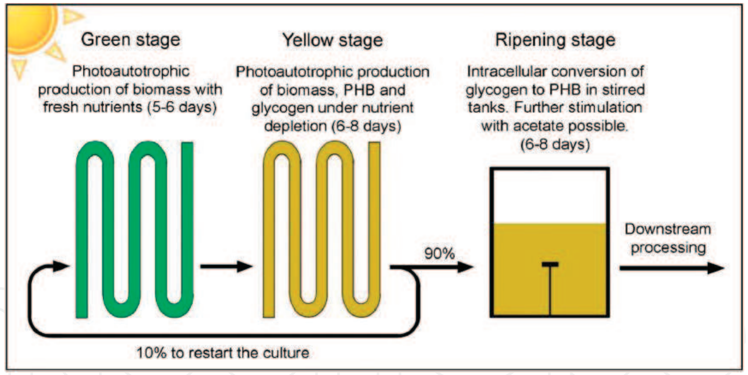
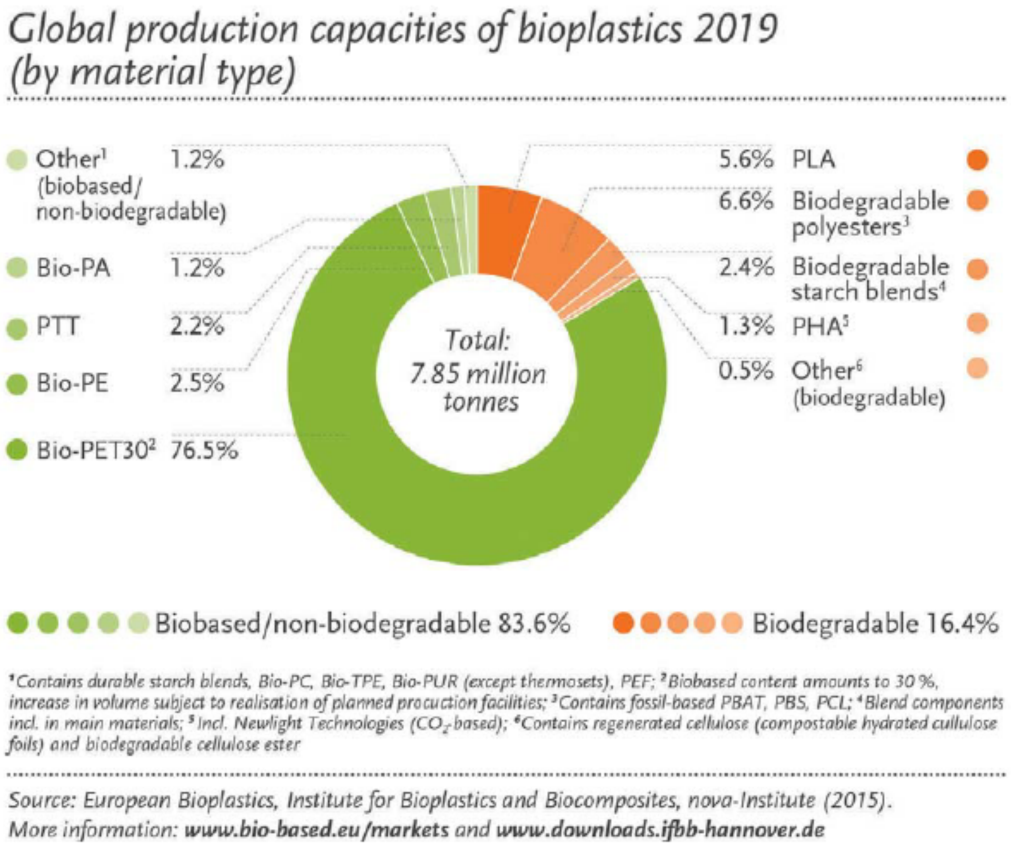
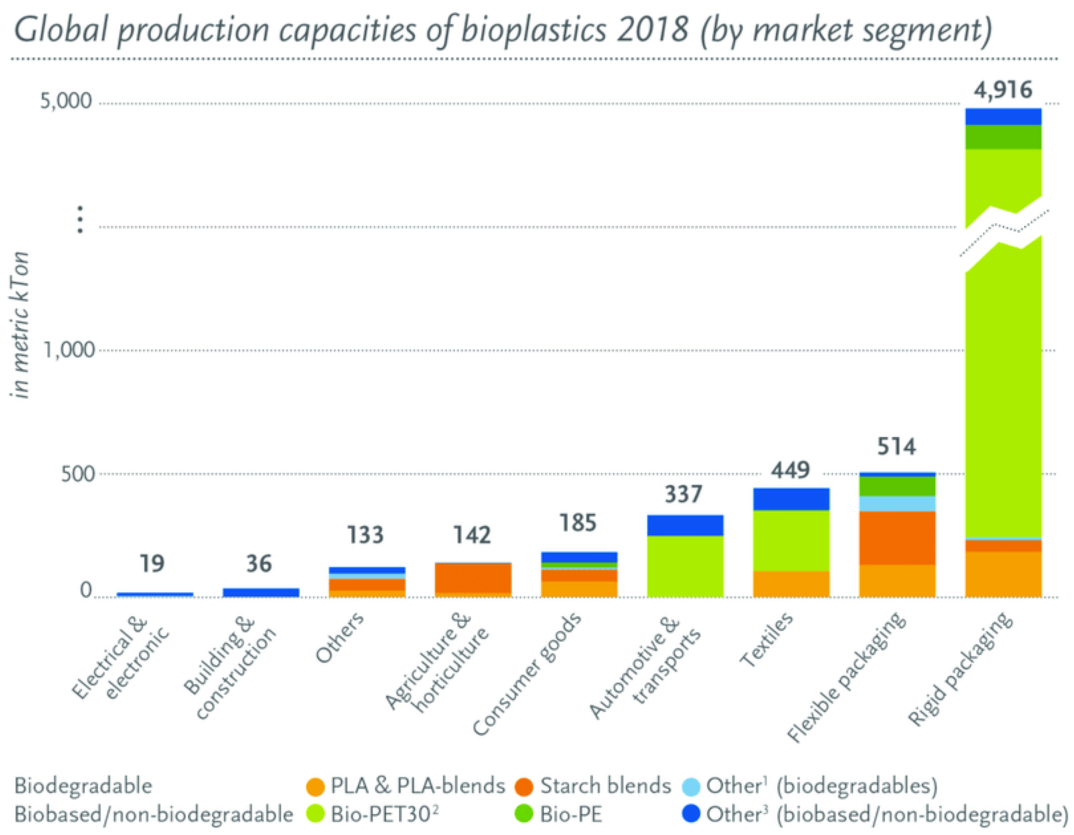


Figure 2.
Operation mode for PHB production from cyanobacteria. The ripening tank is used for PHB production at a later stage, where no CO_2 is consumed, but glycogen gets converted into PHB (reproduced with permission from [18]).

Markl, E., Grünbichler, H. and Lackner, M., 2018. Cyanobacteria for PHB bioplastics production: a review. In *Algae*. IntechOpen.
Koller, M., Maršálek, L., de Sousa Dias, M.M. and Braunegg, G., 2017. Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner. *New biotechnology*, *37*, pp.24-38.

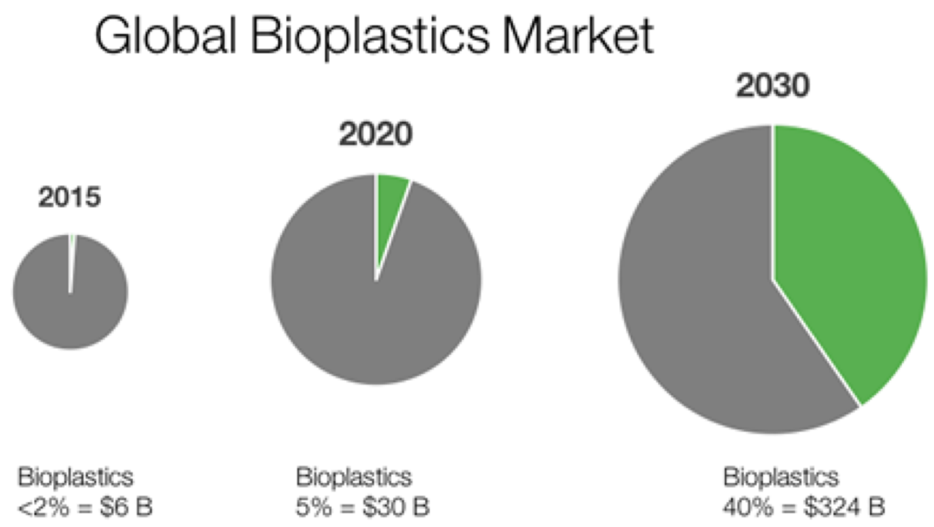
Where do we use bioplastics?



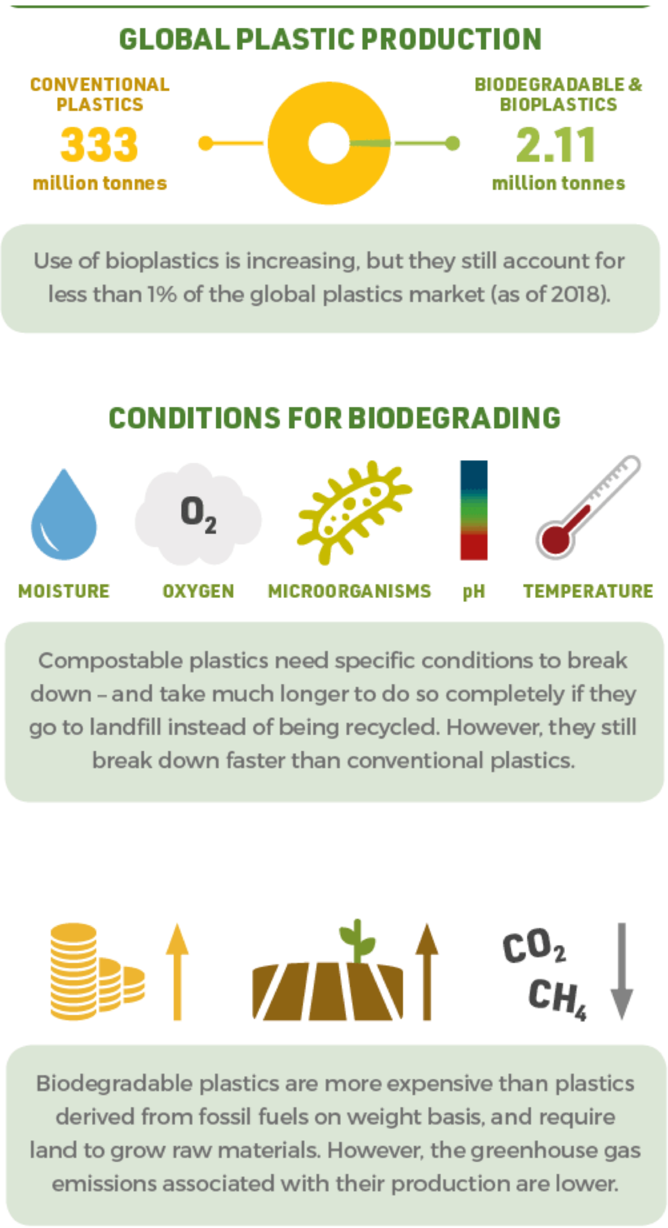


Global production capacities of bioplastics 2018 (by market segments) (European Bioplastics 2014)

Conclusions



[1]Source: Grand View Research 2014, European Bioplastics 2013, BCC Research 2017, Nexant Inc. 2012
[2] https://www.alliedmarketresearch.com/press-release/bioplastics-market.html



References

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Compostable Plastics 101 California Organics Recycling Council Last Updated: 1/1/2011
https://www.cptoolkit.org/Portals/0/Documents/Compostable Plastics 101 Paper.pdf

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