Biopolymers overview

Biopolymers CHEM-E2155

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Schedule

Day	Subject of lecture	Discussion part
08 January	Introduction to the course	
15 January	Biopolymers overview	Reading 1
22 January	Biopolymers for packaging	Reading 2
29 January	Discussion day	Reading 3 & Assignment 1
05 February	Biodegradation 1	Reading 4
12 February	Biodegradation 2	Reading 5
26 February	Discussion day	Reading 6 & Assignment 2
04 March	Chitin, alginates and others	Reading 7
12 March	Proteins	Reading 8
19 March	Discussion day	Reading 9 & Assignment 3
25 March	TBD	Reading 10

Learning Outcomes

After today's course you

- are familiar with common definitions relevant for biopolymers
- know different ways to categorize biopolymers
- Understand the challenges and opportunities of PHAs

Biopolymers

Animal based

Polysaccharides
- Chitin
- Alginates
- Xanthum gum

Proteins
- Collagen
- Gelatin
- α/β-Keratin

Plant based

Polysaccharides
- Starch
- Cellulose
- Hemicelullose
- Pectine

Proteins
- Soy protein
- Gluten

Vegetable fats and oils

Natural rubber

Lignin

From microorganisms

- Polyhydroxyalkanoates
- Pullulan
- Bacterial cellulose

Synthetic

Bio-derived
- Polylactic acid

Oil-based
- Poly(alkylene dicarboxylate)s
- Polycaprolactone

Definitions

Potential for production of sustainable goods

- products made from natural renewable resources
- products that decompose into environmentally friendly constituents

…but they need to provide same results with products made from synthetic materials

Possible challenges:

- costs
- inferior properties

Definitions

No consensus over the exact definition of the generic terms:

- Degradable
- Biodegradable
- Bio-based
- Compostable
- Biopolymer

ISO	International Organization for Standardization
EN	European Norm
ASTM	American Society for Testing and Materials

Degradable Polymers

broad term applied to polymers or plastics that disintegrate by a number of processes (physical disintegration, chemical degradation, and biodegradation by biological mechanisms).

A polymer may be degradable but not biodegradable.

Biodegradable Polymers

degrade under the action of microorganisms such as molds, fungi, and bacteria within a specific period of time and environment.

On its own, the term biodegradable has no clear meaning and creates confusion.

Withdrawn standard ASTM D5488-94de1: biodegradable polymers refer to polymers that are “capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the **enzymatic action of microorganisms** that can be measured by standard tests, over a specific period of time, reflecting available disposal conditions.”

ISO 17088:2012 / EN 13432:2000, EN 14995:2006 / ASTM D6400-12

Michael Niaounakis, *Biopolymers: Processing and Products*, PDL Handbook Series, 1st Edition, Elsevier 2015
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Bio-based

Term focused on the raw materials basis (polymers **derived from renewable resources**).
Raw materials are **renewable if they are replenished by natural procedures** at rates comparable or faster than their rate of consumption

ASTM bio-based materials: “an organic material in which carbon is derived from a renewable resource via biological processes. Bio-based materials include all plant and animal mass derived from carbon dioxide (CO_2) *recently* fixed via photosynthesis, per definition of a renewable resource.”

A bio-based polymer is not *per-se* a **sustainable polymer**; this depends on a variety of issues, including the source material, production process, and how the material is managed at the end of its useful life.

- Not every bio-based polymer is biodegradable
  (bio-based polyethylene or polyamide 11)
- Not every biodegradable polymer is bio-based
  (poly(ε-caprolactone) or poly(glycolic acid))
- Some fall into both categories
  (polyhydroxyalkanoates, PHAs)

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The **bio-based content** of a biopolymer (ASTM D6866-12, ASTM D7026-04):
Number of carbon atoms that come from the short CO_2 cycle
(from biomass as raw material).

Carbon-14 (^{14}C), which has a half-life of about 5700 years, is found in bio-based materials but not in fossil fuels.

"Bio-based materials" refer to organic materials in which the carbon comes from non-fossil biological sources.

A bio-based PET comprises at least about 0.1 dpm/gC (disintegrations per minute per gram carbon) of ^{14}C (decay rate).

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Compostable Polymers

ASTM D6002: as "a plastic which is capable of undergoing biological decomposition in a compost site as part of an available program, such that the plastic is not visually distinguishable and breaks down to carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with known compostable materials (e.g., cellulose) and leave no toxic residue."

This definition drew much criticism, and the standard was withdrawn.

In order for a polymer to be called compostable, it should meet any of the following international standards:

- *ASTM Standard D6400 (for compostable plastics) or*
- *D6868 (for compostable packaging)*
- *CEN standard EN 14995:2006 (for compostable plastics)*
- *or EN 13432:2000 (for compostable packaging)*
- *ISO 17088:2012*

1. **Disintegrate rapidly during the composting;**
2. **Biodegrade quickly under the composting conditions;**
3. **Do not reduce the value or utility of the finished compost and the compost can support plant life;**
4. **Do not contain high amounts of regulated metals or any toxic materials.**

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Biodegradable polymers and compostable polymers are determined **by the rate of biodegradation, disintegration, and toxicity**.

All compostable polymers are by default biodegradable but not vice versa.

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Biopolymers

(or “bioplastic”)

Criteria:

- the source of the raw materials
- the biodegradability of the polymer.

A. Biopolymers made from renewable raw materials (bio-based), and *being biodegradable*

B. Biopolymers made from renewable raw materials (bio-based), and *not being biodegradable*

C. Biopolymers *made from fossil carbon* and being *biodegradable*.

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A. Biopolymers made from renewable raw materials (bio-based), and *being biodegradable*

Can be produced **by biological** systems (microorganisms, plants, and animals), **or chemically synthesized from biological starting materials** (e.g., corn, sugar, starch, etc.):

1. Biopolymers produced by microorganisms, such as PHAs
2. Synthetic polymers from renewable resources such as poly(lactic acid) (PLA)
3. Natural occurring biopolymers, such as starch or proteins; natural polymers are by definition those that are biosynthesized by various routes in the biosphere.

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B. Biopolymers made from renewable raw materials (bio-based), and ***not*** ***being biodegradable***

Can be produced from biomass or renewable resources and are non-biodegradable:

1. Synthetic polymers from renewable resources such as specific polyamides from castor oil (polyamide 11), specific polyesters based on biopropanediol, biopolyethylene (bio-LDPE, bio-HDPE), biopolypropylene (bio-PP) or biopoly (vinylchloride) (bio-PVC) based on bio-ethanol (e.g., from sugar cane), etc.
2. Natural occurring biopolymers such as natural rubber or amber.

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C. Biopolymers *made from fossil carbon* and being *biodegradable*.

Can be produced from fossil fuel, such as synthetic aliphatic polyesters made from crude oil or natural gas, and are certified biodegradable and compostable:

At least partly fossil fuel–based polymers:

1. Poly(ε-caprolactone) (PCL)
2. Poly(butylene succinate) (PBS)
3. Certain “aliphatic-aromatic” copolyesters

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According to *European Bioplastics* a plastic material is defined as a bioplastic if it is either **bio-based, biodegradable**, **or features both properties**:

Biopolymers or Bioplastics:
Biodegradable polymers (e.g., polymers of type A or C)
Bio-based polymers (e.g., polymers of type A or B)

Biopolyethylene derived from sugarcane ("green polyethylene") is nonbiodegradable, but emits less greenhouse gases when compared to fossil-based polyethylene, and is classified as biopolymer.

"Biopolymers are defined as polymers that are derived from renewable resources, as well as biological and fossil-based biodegradable polymers."

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TABLE 1.1 Biodegradable versus Bio-Based Polymers

Origin	Biodegradable	Nonbiodegradable
Bio-based	CA, CAB, CAP, CN, P3HB, PHBHV, PLA, starch, chitosan	PE (LDPE), PA 11, PA 12, PET, PTT
Partially bio-based	PBS, PBAT, PLA blends, starch blends	PBT, PET, PTT, PVC, SBR, ABS, PU, epoxy resin
Fossil fuel-based	PBS, PBSA, PBSL, PBST, PCL, PGA, PTMAT, PVOH	PE (LDPE, HDPE), PP, PS, PVC, ABS, PBT, PET, PS, PA 6, PA 6.6, PU, epoxy resin, synthetic rubber

ABS, acrylonitrile-butadiene-styrene; CA, cellulose acetate; CAB, cellulose acetate butyrate; CAP, cellulose acetate propionate; CN, cellulose nitrate; HDPE, high density polyethylene; LDPE, low density polyethylene; PA 6, polyamide 6; PA 6.6, polyamide 6.6; PA 11, aminoundecanoic acid-derived polyamide; PA 12, laurolactam-derived polyamide; PBAT, poly(butylene adipate-*co*-terephthalate); PBS, poly(butylene succinate); PBSA, poly(butylene succinate-*co*-adipate); PBSL, poly(butylene succinate-*co*-lactide); PBST, poly(butylene succinate-*co*-terephthalate); PBT, poly(butylene terephthalate); PCL, poly(ε-caprolactone); PE, polyethylene; PET, poly(ethylene terephthalate); PGA, poly(glycolic acid), polyglycolide; P3HB, poly(3-ydroxybutyrate); PHBHV, poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate); PLA, poly(lactic acid), polylactide; PP, polypropylene; PS, polystyrene; PTMAT, poly(methylene adipate-*co*-terephthalate); PTT, poly(trimethylene terephthalate); PVOH, poly(vinyl alcohol); PVC, poly(vinyl chloride); PU, polyurethane; SBR, styrene-butadiene rubber.

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TABLE 1.2 Classification of Biopolymers

Biodegradable				Nonbiodegradable
Bio-Based			Fossil-Based	Bio-Based
Plants	Microorganisms	Animals		
Cellulose and its derivatives[1] (polysaccharide)	PHAs (e.g., P3HB, P4HB, PHBHV, $P3HBHH_x$)	Chitin (polysaccharide)	Poly(alkylene dicarboxylate)s (e.g., PBA, PBS, PBSA, PBSE, PEA, PES, PESE, PESA, PPF, PPS, PTA, PTMS, PTSE, PTT)	PE (LDPE, HDPE), PP, PVC
Lignin	PHF	Chitosan (polysaccharide)	PGA	PET, PPT
Starch and its derivatives (monosaccharide)	Bacterial cellulose	Hyaluronan (polysaccharide)	PCL	PU
Alginate (polysaccharide)	Hyaluronan (polysaccharide)	Casein (protein)	PVOH	PC
Lipids (triglycerides)	Xanthan (polysaccharide)	Whey (protein)	POE	Poly(ether-ester)s
Wheat, corn, pea, potato, soy, potato (protein)	Curdlan (polysaccharide)	Collagen (protein)	Polyanhydrides	Polyamides (PA 11, PA 410, PA 610, PA 1010, PA 1012)
Gums (e.g. *cis*-1, 4-polyisoprene)	Pullulan (polysaccharide)	Albumin (protein)	PPHOS	Polyester amides
Carrageenan	Silk (protein)	Keratin, PFF (protein)		Unsaturated polyesters
PLA (from starch or sugar cane)		Leather (protein)		Epoxy
				Phenolic resins

HDPE, high density polyethylene; LDPE, low density polyethylene; P3HB, poly(3-hydroxybutyrate); $P3HBHH_X$, poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate); P4HB, poly(4-hydroxybutyrate; PBA, poly(butylene adipate); PBS, poly(butylene succinate); PBSA, poly(butylene succinate-*co*-adipate); PBSE, poly(butylene sebacate); PC, polycarbonate; PCL, poly(ε-caprolactone); PE, polyethylene; PEA, poly(ethylene adipate); PES, poly(ethylene succinate); PESA, poly(ethylene succinate-*co*-adipate); PESE, poly(ethylene sebacate); PET, poly(ethylene terephthalate); PFF, poultry feather fiber; PGA, poly(glycolic acid), polyglycolide; PHA, polyhydroxyalkanoate; PHBHV, poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate); PHF, polyhydroxy fatty acid; PHH, poly(3-hydroxyhexanoate); PLA, poly(lactic acid), polylactide; POE, poly(ortho ester); PP, polypropylene; PPF, poly(propylene fumarate); PPHOS, polyphosphazenes; PPS, poly(propylene succinate); PTA, poly(tetramethylene adipate); PTMS, poly(tetramethylene succinate); PTSE, poly(tetramethylene sebacate); PTT, poly(trimethylene terephthalate); PVC, poly(vinyl chloride); PVOH, poly(vinyl alcohol); PU, polyurethane.

[1] *Acetyl cellulose (AcC) is either biodegradable or nonbiodegradable, depending on the degree of acetylation. AcCs with a low acetylation can be degraded, while those with high substitution ratios are nonbiodegradable.*

Biopolymers can also be classified based …

on how they respond to heat:

- **Thermoplastics**
- **Thermosets**
- **Elastomers**

The volume of bio-based thermoset biopolymers exceeds the volume of bio-based thermoplastic biopolymers

on their composition:

- Blends
- Composites
- Laminates.

Biocomposites: biopolymers or synthetic polymers reinforced with natural fibers, such as sisal, flax, hemp, jute, banana, wood, and various grasses, and/or fillers and additives.
Novel biocomposites are based on a biodegradable matrix polymer reinforced with natural fibers.

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Types and chemistry of biopolymers

- chemical synthesis →
  - PLA obtained by polymerizing lactic acid, which is produced by fermenting saccharides and starch derived from corn, potato, and sugarcane.
  - Poly(butylene succinate) resins, produced from succinic acid derived from starch and 1,4-butane diol.
  - Polyamide 11, produced from castor oil.
- microorganism production →
  - poly-3-hydroxybutyrate type resins
  - copolymers of 3-hydroxybutyrate and 3-hydroxyhexanoate
- natural →
  (derived from the biomass, i.e., from plants)
  - cellulose acetate
  - esterified starch
  - chitosan-cellulose-starch
  - starch-modified polyvinyl alcohol

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Polyhydroxyalkanoates (PHA)

Koller, M.; Mukherjee, A. A New Wave of Industrialization of PHA Biopolyesters. Bioengineering 2022, 9, 74. https://doi.org/10.3390/bioengineering9020074

Li, Z.; Yang, J; Loh X.J. Polyhydroxyalkanoates: opening doors for a sustainable future. NPG Asia Materials 2016 8, e265; doi:10.1038/am.2016.48

Raza, Z.A.; Abid, S.; Banat, I.M. Polyhydroxyalkanoates: Characteristics, production, recent developments and applications. International Biodeterioration & Biodegradation 2018, 126, 45–56. doi: 10.1016/j.ibiod.2017.10.001

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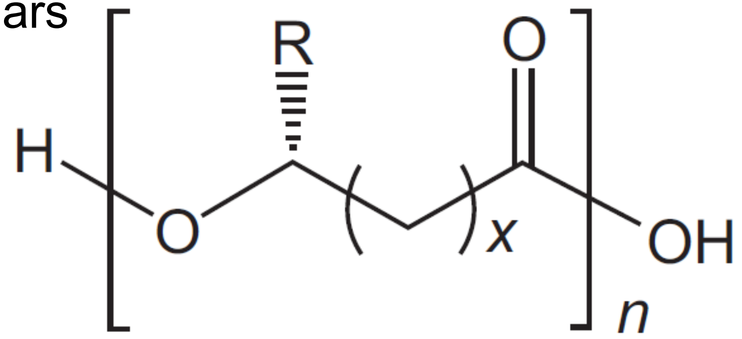
Polyhydroxyalkanoates (PHAs)

- PHAs are polyesters produced in nature by microorganisms (prokaryotic and eukaryotic), including through bacterial fermentation of sugars or lipids
- two groups of bacteria with regards to PHAs production
  - requiring limitation of a nutrient such as phosphorous, nitrogen, oxygen or magnesium to accumulate PHAs; no accumulation during growth phase
  - accumulates PHAs during the growth phase and do not require any nutrient limitation



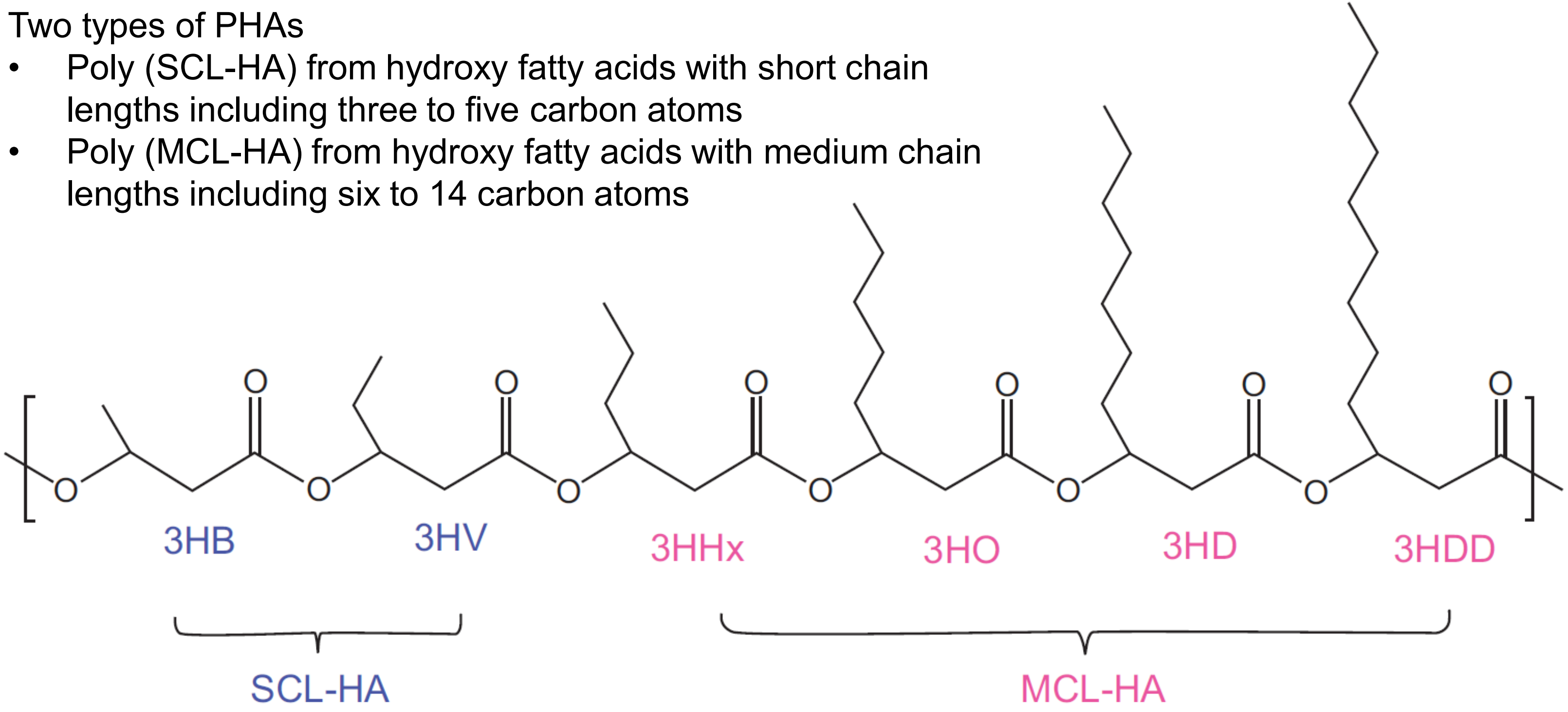
Polyhydroxyalkanoates

- Lemoigne first discovered PHA in *Bacillus megaterium* in the form of poly (3-hydroxybutyrate) (PHB) in 1925/6
- PHAs serves intracellular carbon and energy storage purposes
- despite the discovery of more than 150 different hydroxyalkanoate (HA) building blocks that constitute the PHA biopolyester family, only a limited number of PHA copolymer types have reached industrial maturity

Polyhydroxyalkanoates

Two types of PHAs

- Poly (SCL-HA) from hydroxy fatty acids with short chain lengths including three to five carbon atoms
- Poly (MCL-HA) from hydroxy fatty acids with medium chain lengths including six to 14 carbon atoms



Some commonly synthesized short-chain-length PHA monomers (SCL-HA) and middle-chain-length PHA monomers (MCL-HA). 3HB: 3-hydroxybutyrate, 3HV: 3-hydroxyvalerate, 3HHx: 3-hydroxyhexanoate, 3HO: 3-hydroxyoctanoate, 3HD: 3-hydroxydecanoate, 3HDD: 3-hydroxydodecanoate.

PHA development

- ecological concerns of fossil plastics and limitations of fossil resources motivated research towards the industrial use of PHA biopolymers
- skyrocketing crude oil prices in the 1970s prompted the first commercialization efforts
- however, much of that effort slowed down after the recovery of crude oil prices
- Price and availability still primary obstacles towards commercialization of PHAs

https://www.nytimes.com/2008/03/04/business/worldbusiness/04oil.html

PHA development

- calculations based on several life cycle studies estimate that replacement of 1 kg fossil plastic by PHA could salvage on average CO_2 emissions by 2 kg and around 30 MJ of fossil resources on an energy basis
- material properties of PHAs depend on the type and distribution of various monomeric building blocks
- versatile group of biomaterials, with characteristics that range from elastomeric to semicrystalline thermoplastic-like polymers
- The material properties of PHAs do not exactly match those of the fossil-based competitors
- → PHAs were not drop-ins for fossil plastics

PHA production

- main drawback is the high cost associated with fermentative production
- major factors affecting the cost of production include the type of carbon source, running cost of fermentation, and process productivity
- PHAs contents in the cell biomass are very important for economical extraction process
- also, the selection of a hyper productive microorganism is equally important
- average cost of PHB production (100,000 ton/year scale) were reported to be between 2.6 and 6.69 USD/kg

What is the price of common synthetic polymers?

An overview on PHAs production strategies.

Sr.No.	Carbon source	Bacterial strain	Fermentation mode	Type of polymer	Limiting factor	CDW (g/l)	Accumulation of PHA of CDW	Extraction method	Yield (g/l)	Ref.
1	Triglycerides	*Pseudomonas resinovorans* NRRLB-2649	Fed-batch	mcl	NA	3.3	45%	Solvent	1.1–2.1	(Ashby and Foglia, 1998)
2	Hexadecane	*P. aeruginosa* ATCC 10145	Continuous	mcl	Nitrogen	1	7.5%	NA	NA	(Chayabutra and Ju, 2001)
3	Glucose	*Bacillus cereus*	Batch	scl	NA	3.4	47.9%	Solvent	1.19	(Devi et al., 2015)
4	Octanoate	*P. oleovorans* ATCC 29347	Continuous	mcl	Carbon Nitrogen	NA	10.1% 56.1%	NA	NA	(Durner et al., 2000)
5	Technical oleic acid Waste free fatty acids from soybean oil Waste frying oils Glucose	P. aeruginosa 42A2 NCIB 40045	Batch	mcl/lcl	Nitrogen	3.2 NA	54.6% 66.1% 29.4% 16.8%	Solvent	NA	(Fernandez et al., 2005)
6	Fatty acids	*P. putida* Bet001	Batch	mcl	Nitrogen	NA	49.7–68.9%	Solvent	10.12–15.45	(Gumel et al., 2014)
7	Glucose Soybean oil	*P. stutzeri* 1317	Batch	mcl	NA	2.3 2.7	52% 63%	Chloroform- sodium hypochlorite method	NA	(He et al., 1998)
8	Decanoate	*P. aeruginosa* IFO 3924 *P. aeruginosa* PAO 1 *P. aeruginosa* IFO 3755 *P. aeruginosa* IFO 14164	Batch	mcl	Nitrogen	2.2 2 3.1 2.8	23% 10% 22% 21%	Solvent	NA	(Hori et al., 2002)
9	Terephthalic acid	*P. putida* GO16 *P. putida* GO19 *P. frederiksbergensis* GO23	Batch	mcl	Nitrogen	1	27% 23% 24%	NA	0.25 0.25 0.27	(Kenny et al., 2008)
10	10-undecenoicacid and 10-undecynoic acid	*P. putida* KCTC 2407	Batch	mcl	NA	0.40–0.94	1.8–37.4%	Solvent	0.01–0.32	(Kim et al., 2000)
11	n-alkanes and 1-alkenes	*P. oleovorans* ATCC 29347	Batch	mcl	Nitrogen	2	25%	Solvent	NA	(Lageveen et al., 1988)
12	Palm oil	*P. aeruginosa* IFO3924	Batch	mcl	Nitrogen	1.8–2.7	16-39%	Solvent	0.28–1.06	(Marsudi et al., 2008)
13	Glucose	*Lysinibacillus sphaericus* GBS1 *L. sphaericus* GBS2 *L. sphaericus* GBS3 *L. sphaericus* GBS4 *L. sphaericus* GBS5 *L. sphaericus* GBS6	Batch	scl	NA	NA	60% 50% 33% 14% 66% 70%	Chemical Digestion	1.2 0.9 1.3 0.2 0.12 1.3	(Biradar et al., 2015)
14	Commercial glycerol Waste glycerol	*Cupriavidus necator* DSM 545	Fed-batch	scl	Nitrogen	NA	62% 52%	Solvent	51.2 38.1	(Cavalheiro et al., 2009)
15	*n*-octane	*P. oleovorans* GPo1	Fed-batch	N.A	Nitrogen	37.1	33%	NA	12.1	(Preusting et al., 1993)
16	Sugarcane liquor	*P. fluorescence* A2a5	Batch	scl	Nitrogen	32	70%	Solvent	22	(Jiang et al., 2008)
17	Waste cooking oil	*Pseudomonas* sp. PS1 *Pseudomonas* sp.	Batch	N.A	Nitrogen	NA	NA	Solvent	2.3 2.7	(Prasad and Sethi, 2013)
18	Crude palm oil kernel oil Crude palm oil Palm kernel oil Palm olein Cooking oil Olive oil Coconut oil Sunflower oil	*C. necator* H16	Fed-Batch	scl co-polymer (P3HB & P3HB-co-3HV)	Nitrogen	5.0 4.6 5.6 5.2 5.4 4.9 4.7 4.4	67% 75% 77% 70% 78% 80% 72% 76%	Solvent	3.4 3.5 4.3 3.6 4.2 3.9 3.3 3.4	(Lee et al., 2008)
19	Pigeon pea waste Paddy waste Waste frying oil Sugarcane bagasse Rice bran	*P. aeruginosa*	Batch	N.A	NA	NA	39% 41% 42% 60% 48%	NA	NA	(Khandpur et al., 2012)

International Biodeterioration & Biodegradation 2018, 126, 45–56. doi: 10.1016/j.ibiod.2017.10.001

PHA production

Extraction of PHAs from bacterial cells:

- solvent extraction
- flotation method
- chemical or enzymatic digestion of cell components
- supercritical fluid extraction
- aqueous two-phase extraction

Further downstream and purification processes https://youtu.be/YWs_VVLNWC0

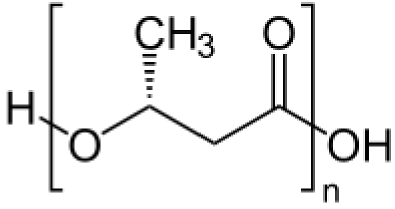
PHA production

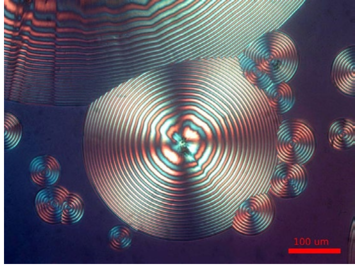
- to lower the price different materials and side-products can be used as carbon sources: whey, wheat, rice bran, starch, sugar-cane molasses, vegetable oils
- current annual production <10 kt
- however, capacity expansions of over 1.5 million t have already been announced for the next 5–10 years (an additional 1 million t are in the planning stages)
- (estimated global plastic production: roughly 400 Mt per year)

most prominent PHAs

- homopolyester poly(3-hydroxybutyrate) (P(3HB))
- the copolyesters poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (P(3HB-co-3HV)), poly(3- hydroxybutyrate-co-4-hydroxybutyrate) (P(3HB-co-4HB)), and poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (P(3HB-co-3HHx))
- to a minor extent, the homopolyester poly(4-hydroxybutyrate) (P(4HB)) and some medium-chain-length PHA (mcl-PHA) copolyesters

P(3HB) or PHB





poly(3-hydroxybutyrate) (homopolyester)

constitutes the by far best-studied representative of the PHA family; produced by the largest number of microbes

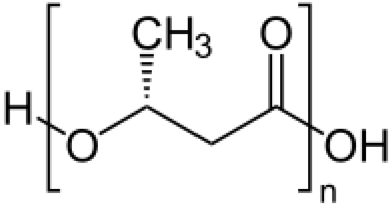
Cons:

- very narrow melt processing window since its melting temperature is close to its degradation temperature
- highly crystalline; therefore, it has a low elongation at break and is brittle
- lower biodegradability rates compared to other types of PHA

Pros:

- production of hard, creep-resistant items, which do not change their properties over a broad temperature range even when stored for several years
- outperforms many competing petrochemical plastics in UV resistance and mechanical stability

P(3HB) or PHB

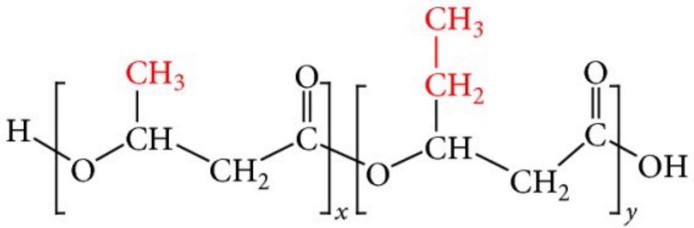


Applications:

- films, coatings, injection molded products
- 3D-printed objects
- biomedical application (implants, artificial esophagus)
- replacement for LD-PE in electronics

DOI: 10.1201/b16588-13

P(3HB-*co*-3HV)



poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) copolyester

- can be produced by feeding appropriate 3HV precursors
- with increasing 3HV content, melting point T_m decreased: 170 °C for P(3HB) and 140 and 130 °C for the two P(3HB-*co*-3HV) grades, degree of crystallinity (80, 60, and 35%), tensile strength (40, 25, and 20 MPa), flexural modulus (3.5, 1.2, and 0.8 GPa), elongation at break (8, 20, and 50%), and impact strength (60, 110, and 350 J/m))
- lower T_m broadens processing windows, making them suitable especially for extrusion, injection, and blow molding, which enabled more applications of injection-molded parts, bottles, extruded sheets, films, fibers, and coated paper

Summary questions

- What is the difference between degradable and biodegradable?
- Name a fossil-based biodegradable polymer.
- Name a biobased non-degradable polymer.
- What are PHAs?
- Which PHAs are used industrially already?

Reading 2

Title: Biopolymer-Based Sustainable Food Packaging Materials: Challenges, Solutions, and Applications
Authors: Perera *et al.*
Foods **2023,** 12, 2422

Read before lecture on January 22:

- Chapters 1-5
- Chapters 6.1.1 and 6.1.2
- Browse through tables 1 & 2

Reading discussion peer grading

Legend:

present:	no = 0; yes = 1	
camera on:	no = 0; yes = 1	
active participation in discussion:		little to none = 0; ok = 1; very good = 2
active participation in preparing Padlet content:		little to none = 0; ok = 1; very good = 2

points	grade
50-45	5
40-44	4
35-39	3
30-34	2
25-29	1
0-24	0

Group 1	Discussion of Reading 1				
	present	camera on	active participation in discussion	active participation in preparing Padlet content	score
Name1					0
Name2					0
Name3					0
Name4					0
Name5					0

Reading 1 discussion

Title: Biopolymers: overview of several properties and consequences on their applications
Authors: K. Van de Velde & P. Kiekens
Polymer Testing **2002**, 21, 433–442

Discussion items:

- Which (main) polymers are discussed in this article and how are the similar or how do they differ chemically rom each other?
- Which material properties are discussed? How do they correlate with each other?
- How are those properties important for composite materials?

Instructions:
Write your names, summary and updated figures in e.g. PowerPoint. Save the text as image file (.jpg) and upload it to the Padlet page:
https://padlet.com/michaelhummel/CHEME2155_2024

Group 1	
Babak	Abdi
Sagar	Gurung
Carl-Alfons	Antson
Anupama	Bhandari
Jianhui	Feng

Group 2	
Giorgia	Donatoni
Andrea	Bonvini
Christian	Zimmermann
Jan	Kantelinen
Azad	Karis

Group 3	
Helmi	Hanninen
Eva	González Carmona
Sara	Hautojärvi
Laura	Ahvenjärvi
Nikita	Jamkin

Group 4	
Laura	Ferrer Pascual
Trung	Luong
Rasmus	Huttunen
Patrick	Hyvärinen
Parham	Koochak

Group 5	
Muhammad	Umer
Asfar	Khan
Sardar	Hayat
Kaisla	Lehtipuu
Anneli	Lepo

Group 6	
Daniel	Schröfl
Clemens	Hellmig
Emilia	Ikävalko
Asle	Berget
Lukas	Fliri

Group 7	
Henna	Koponen
Sampsa	Mäenpää
Mikael	Nortes
Veera	Ollikainen
Tiina	Pasanen

Group 8	
Johannes	Peace
Ilari	Peltonen
Sayoojya	Prasad
Tiinamari	Seppänen
Nissa	Solihat

Group 9	
Eveliina	Palo
Oona	Hanska
Joona	Pystynen
Luka	Louhi
Eetu	Varttila

Group 10	
Jere	Pätsikkä
Krisnadewi	Suciati
Possathornwalee	Prasomsri
Öykü	Sahintas
Yuxuan	Sun

Group 11	
Anni	Raulahti
Anniina	Tamminen
Elsa	Vuorenmaa
Mimi	Tran
Mariel	Mylly

Group 12	
Chamodya	Ranawaka Arachchige
Elizaveta	Tapaila
Moa	Vesterlund
Anitha	Venkatramani
Konsta	Vainikainen

Group 13	
Anastasia	Tervo
Timo	Tuoresjärvi
Julia	Turunen
Fatemeh	Yahyaeian Balouchi
Can	Yücel