Alternatives to Polyethylene Packaging for Frozen Kelp

Eliana Blum, Erin Xavier, Kay Elofson,
Sara Susanto, Kaydren Orcutt, Frank Bernal

01

INTRODUCTION

Background, Inspiration, & Approach

02

STRATEGIES

Explanation of Strategies 1, 2, & 3

03

DISCUSSION

Comparison of Strategies 1, 2, & 3

04

NEXT STEPS

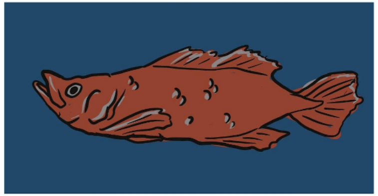
Proposed Solution & Timeline

Noble Oceans Farm

Image from https://www.walmart.com/ip/Vacuum-Sealer-Bag-HURRISE-Vacuum-Sealer-Food-Storage-Saver-Bag-w-Unique-Multi-Layer-Construction/194601508?wmlspartner=wlpa&selectedSellerId=101006085

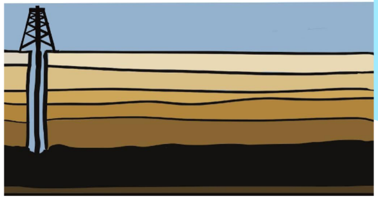
- Noble Ocean Farms is a startup regenerative kelp farming company in Cordova, Alaska
- Their goal is to process and package their kelp for consumer use in order to aid food insecurity
- **Initial brief:** Vacuum sealable package that can be frozen and compost in 6 months or less

Background: How to make plastic bags



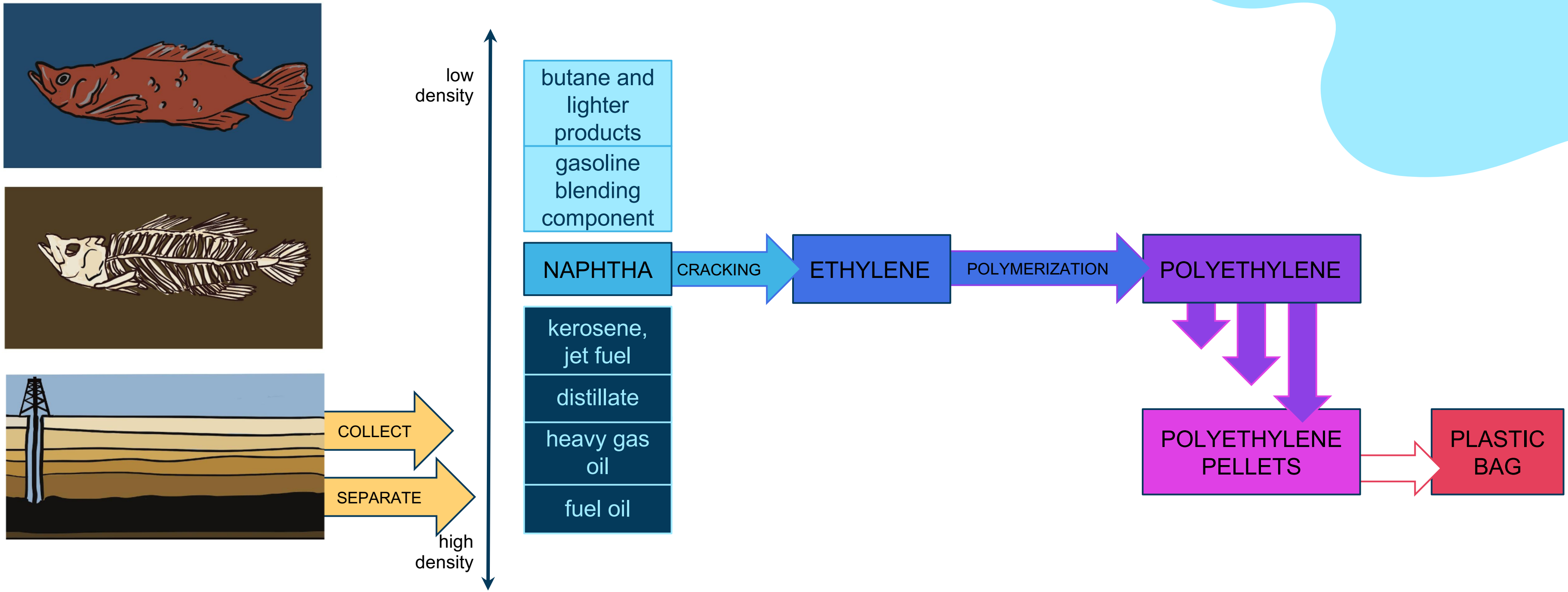
Ocean life 300 - 400 million years ago dies.

Over millions of years, remains buried deeper and deeper where the pressure and heat turn it into oil and natural gas.



Today we drill down and collect the oil and gas to use for transportation, industrial applications, and power.

Background: How to make plastic bags



Bad Actors

Common name or trade name	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
Polyethylene, HDPE, LDPE, and monomers	**3**	DG	DG	3	3	3	*3*	*2*	**1**

Bad Actors	DG = Data Gap	4 = Low Hazard	3 = Moderate Hazard	2 = High Hazard	1 = Very High Hazard

Background: The Problem with Plastics

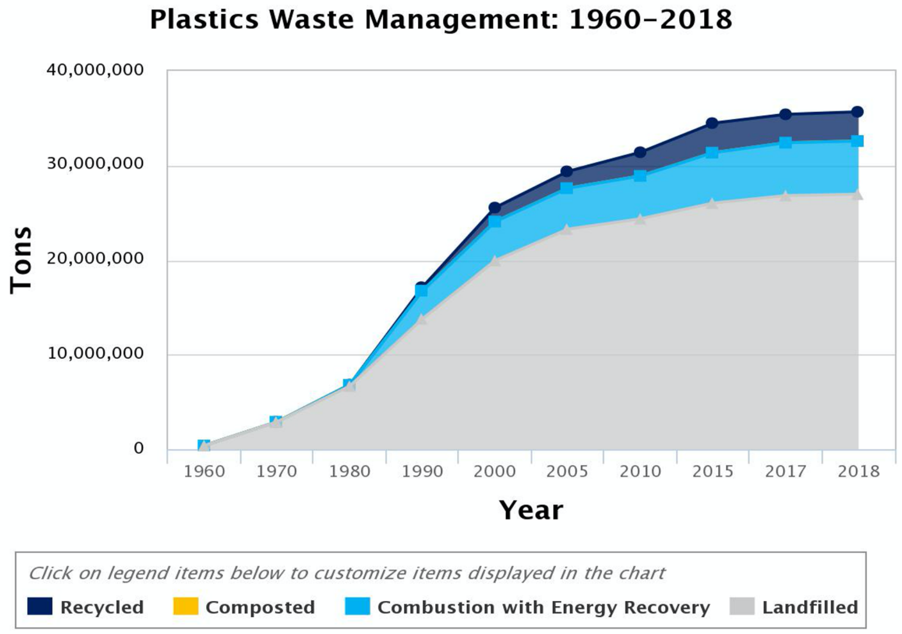


Figure from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

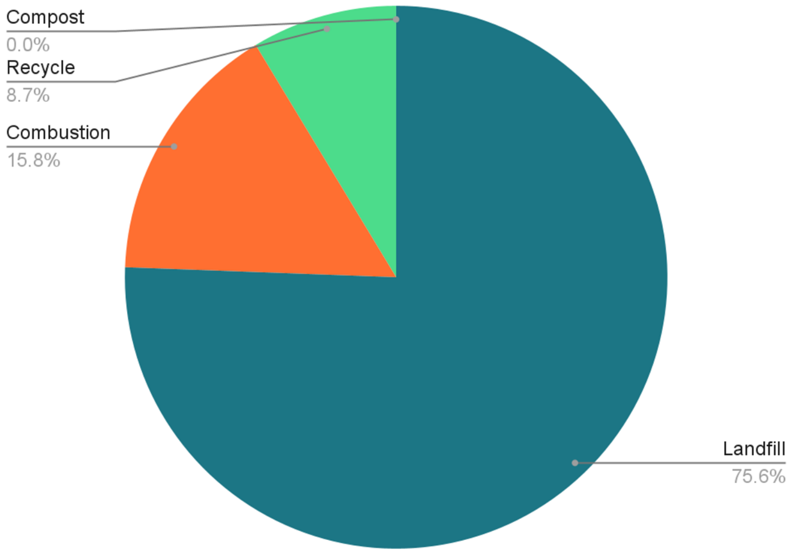
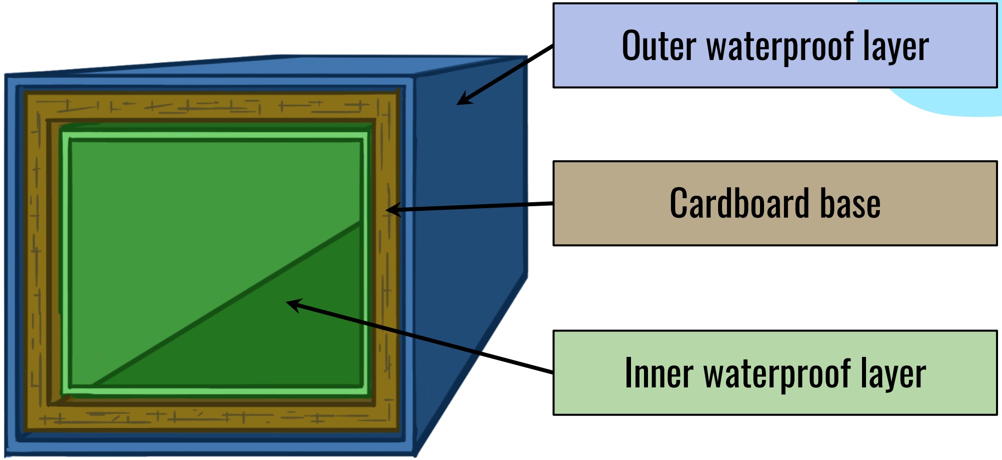


Figure adapted from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data#PlasticsTableandGraph

Inspiration: What is also edible, frozen, and packaged?

Image from https://www.heb.com/product-detail/ben-amp-jerry-s-red-velvet-cake-ice-cream/1456681



Vacuum Sealing Requirement

Traditionally, frozen seaweed is vacuum sealed to preserve freshness and prevent freezer burn

Initial research showed incompatibility between vacuum sealing and researched bioplastics

So, do we need it?

SeaGrove Kelp does not vacuum seal and has no issues. Kelp is frozen in bulk in a blast chiller

Vacuum sealing compatibility is therefore **no longer a requirement for our polymers**

Image from https://cottagecityoysters.com/new-products/frozen-kelp-cubes

Criteria for a Successful Greener Solution

Barrier Performance:
Water & gas-tight

Health & Environmental Performance:
Biodegradability/compostability

Working Temperature Range:
Stable at freezing, room temp, and melting temperatures

Mechanical Properties:
Flexible & strong

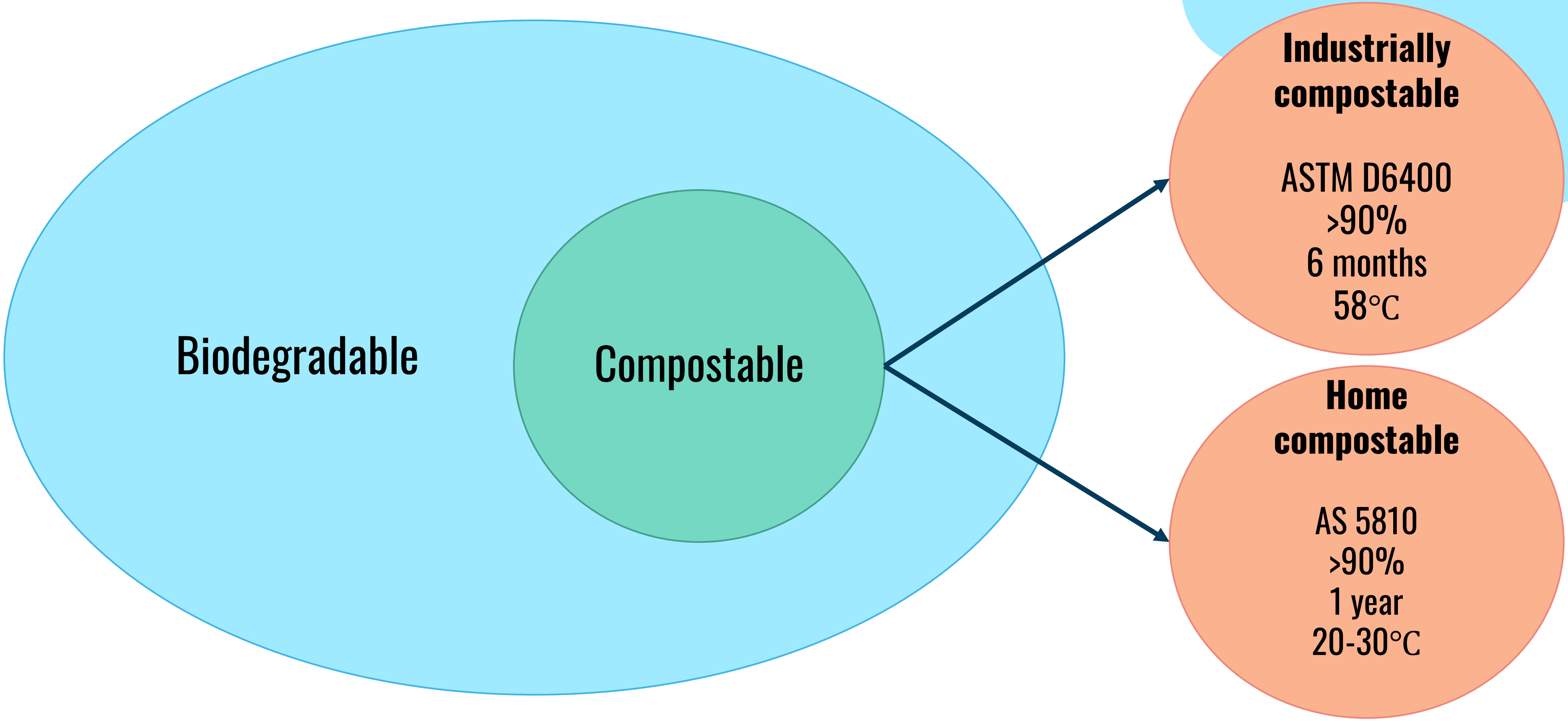
Main Technical Criteria Standards

	Barrier Properties				Working Temperature Range			Mechanical Properties	
Name of criteria	Oxygen Permeability	Water Permeability	Cobb60	Kit Value	Glass Transition Temperature	Melting Temperature	Degradation Temperature	Tensile Strength	Elongation at Break (%)
Definition	How much oxygen can penetrate a barrier through time	How much water can penetrate a barrier through time	How much water is absorbed by a material over time	How repellent a material is to liquid	Temperature at which a material transitions to brittle from ductile	Temperature in which a material changes phase from solid to liquid	Temperature in which a material loses fundamental properties	Strength a material can withstand before fracture	Elongation a material can endure before fracture

Main Technical Criteria Standards

	Barrier Properties				Working Temperature Range			Mechanical Properties	
Name of criteria	Oxygen Permeability	Water Permeability	Cobb60	Kit Value	Glass Transition Temperature	Melting Temperature	Degradation Temperature	Tensile Strength	Elongation at Break (%)
Good	Less than 20 $g/m^2/24$ hrs	Less than 1 $g/m^2/24$ hrs	Less than 10 g/m^2	7 or greater	Below 5 °C	At least 40°C below Degradation Temp	Above 140°C	Above 10 MPa	At least 100%
Okay	20 - 100	1 - 50	10 - 50	5 - 6	5 - 60	20 - 40 difference	100 - 140	5 - 10	7% to 100%
Bad	Greater than 100	Greater than 50	Greater than 50	Less than 5	Greater than 60	Less than 20 different	Less than 100	0 - 5	Less than 7%

Not All Biodegradable Materials are Compostable



Strategies Overview

Strategy 1

Bioplastics to replace traditional plastics

Strategy 2

Bioplastic coating/laminate attached to structural material

Strategy 3

Separate inner bioplastic bag with an outer sturdy structural container

Materials: **Biodegradable Bioplastics**

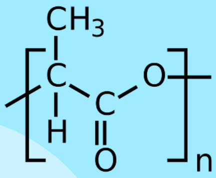
PLA

Polylactic Acid

Made from corn, among other sources

Already in commercial use

Industrially compostable

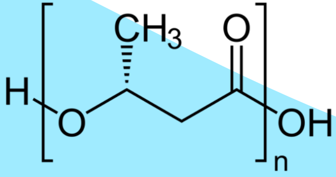


PHA

Polyhydroxyalkanoates

Group of polyesters **grown using microorganisms**

Potentially narrower thermal processing window



PBS

Polybutylene succinate

May be fossil or bio-based

Durable, but **poor barrier properties**

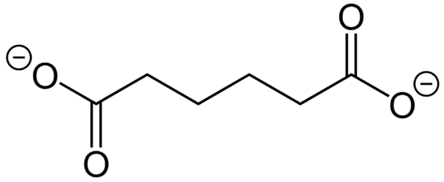


Image from: https://key0.cc/freepng/download/83648_Sweet-Corn-Drawing-At-Corn-Clipart,

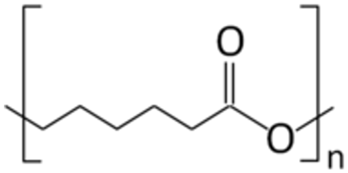
Materials: **Biodegradable Plastics** *(Additives)*

PCL

Polycaprolactone

Biodegradable **fossil-based** polymer

Decreases water permeability and increases mechanical strength

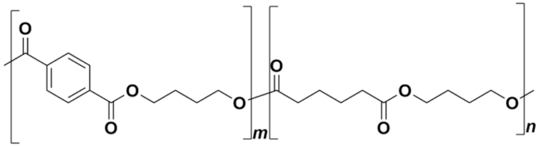


PBAT

Polybutyrate adipate terephthalate

Biodegradable **fossil-based** polymer

Increases mechanical strength

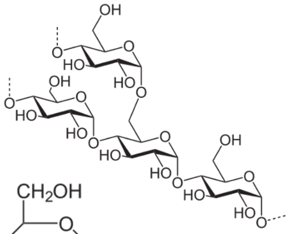


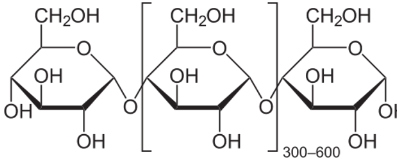
TPS

Thermoplastic starch

Biodegradable **bio-based** polymer

Lowers production cost and increases permeability





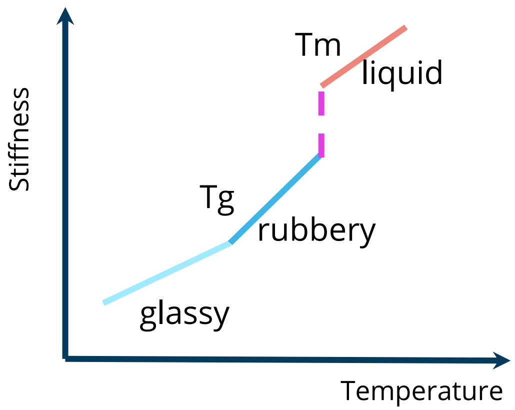
Technical performance: **Barrier properties**

	O_2 permeability (g/m²/24 hrs)	H_2O permeability (g/m²/24 hrs)
PLA	3.5 - 15 cm^3•mm/m^2 day atm	12.6
PHA (PHB)	13.4	2.4
PBS	0.97 - 0.99 PO × 10^{16} [mol/m·s·Pa]	2.73 - 2.75 PWV × 10^{12} [mol/m·s·Pa]
PCL	775	177
PBAT	600 mL/m^2/d/bar	240
TPS	3.53×10^{-5} – 1.69×10^{-1} g•mm•m^{-2} h^{-1}•kPa^{-1}	0.34 – 0.65 g•mm•m^{-2} h^{-1}•kPa^{-1}
LDPE	19.2	0.037

Technical performance: **Working Temperature Range**

	Degradation (°C)	Melting (°C)	Glass transition (°C)
PLA	300	175	50-80
PHA (PHB)	220	180	4
PBS	600	115	-29
PCL	380	60	-60
PBAT	338	120	-30
TPS	350	150	-75
LDPE	370 - 510	110	-30

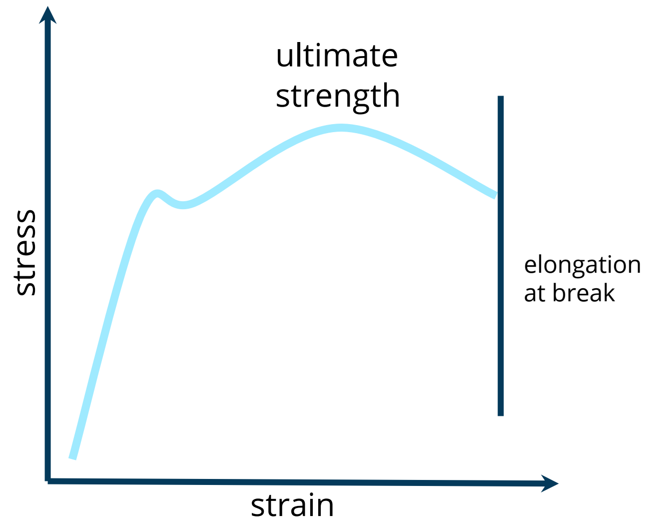
Phase Changes with Temperature



Technical performance: **Mechanical Properties**

	Tensile Strength (MPa)	Elongation at Break (%)
PLA	50	3.3
PHA (PHB)	40	4.3
PBS	28-31	14.6
PCL	20-42	1675
PBAT	18-25	580-800
TPS	6	60
LDPE	10 - 15	300 - 500

Strength of Materials



Strategy 1: **Health and Environmental Performance**

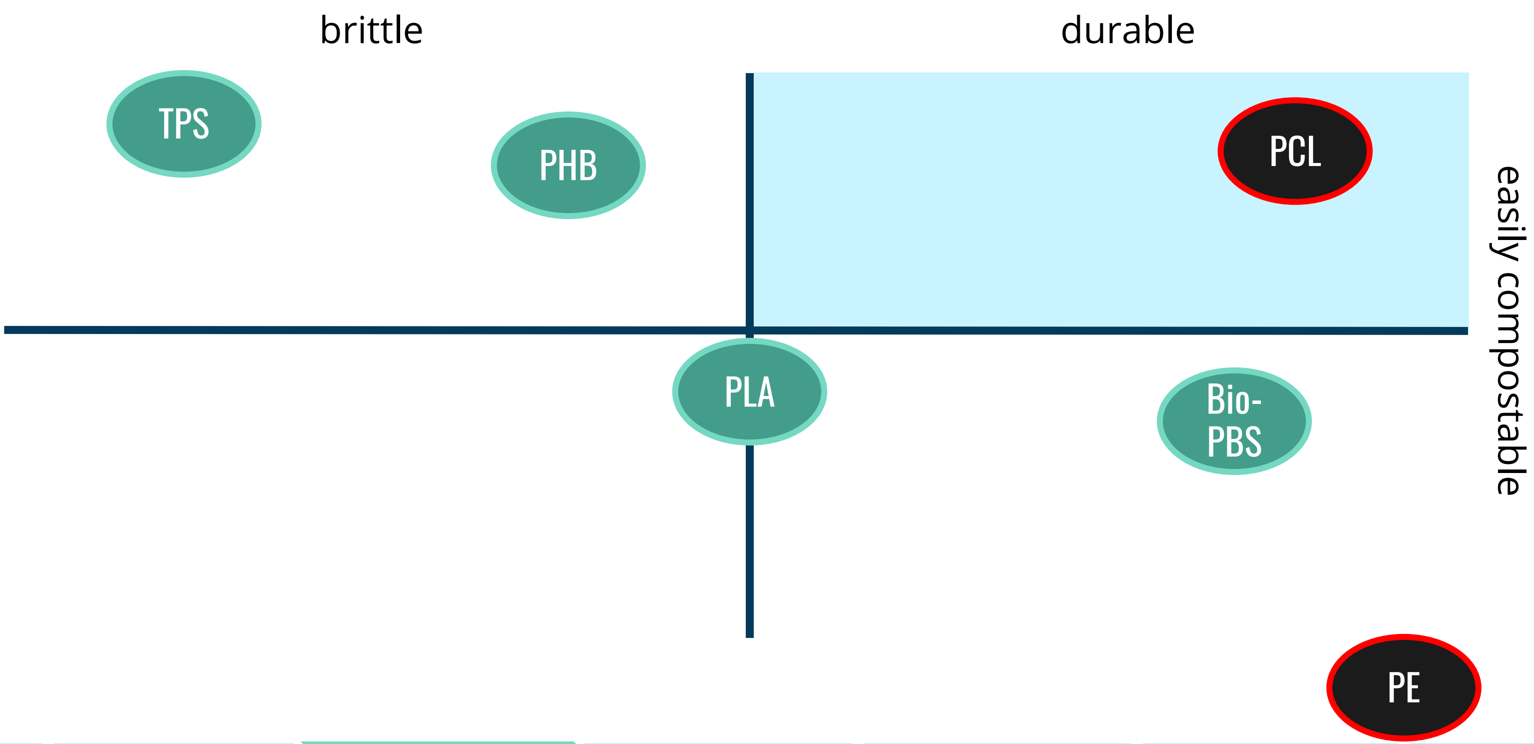
	Home Compostable	Industrially Compostable
PHA (PHB)	Y	Y
PLA	N	Y
PBS	Y*	Y
PCL	Y	Y
PBAT	Y*	Y
TPS	Y	Y
HDPE/LDPE	N	N

Strategy 1: **Health and Environmental Performance**

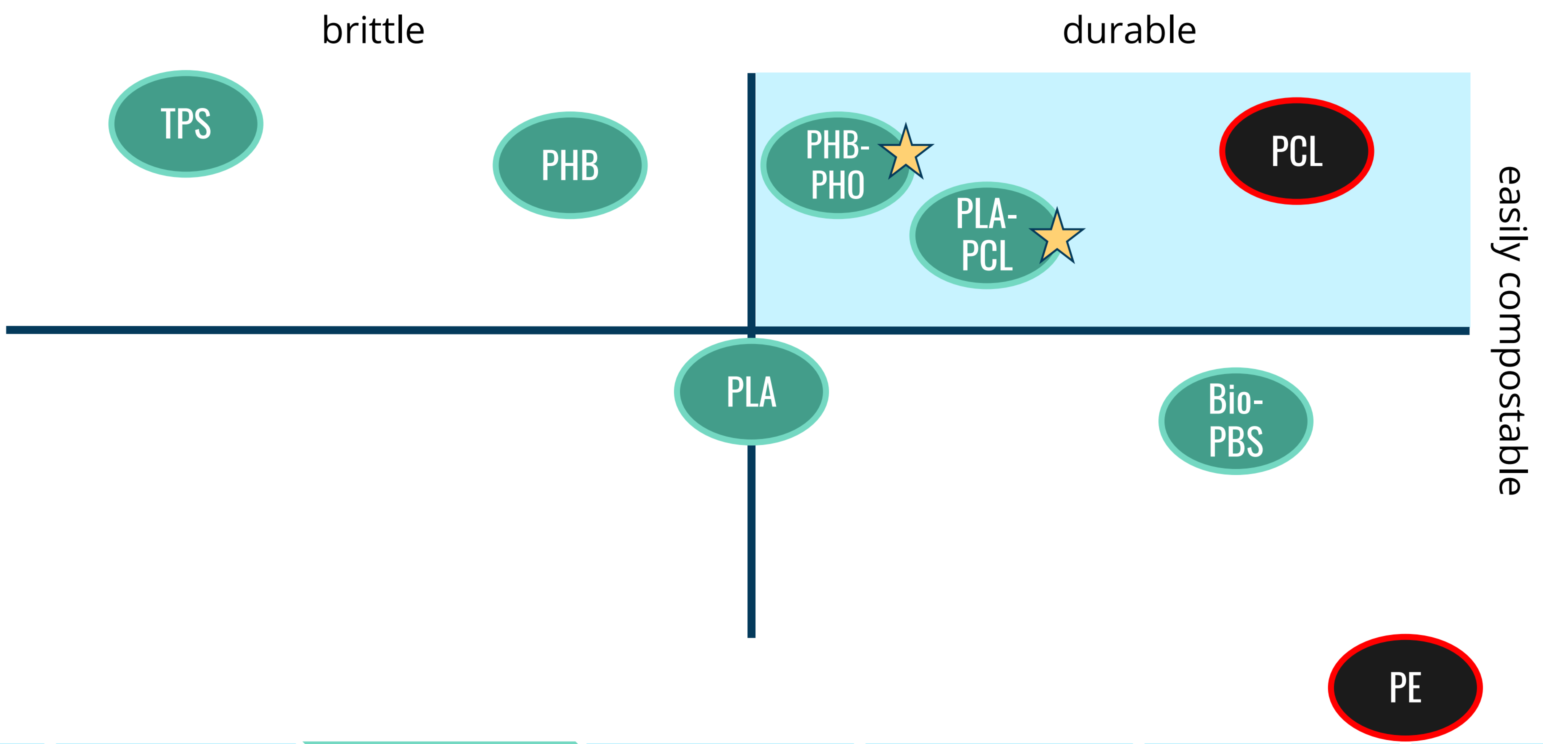
	PHA (PHB)	PLA	PBS	PCL	PBAT	TPS	Polyethylene
Carcinogenicity	4	4	3	4	DG	3	3
Endocrine Activity	DG	4	DG	DG	DG	3	DG
Systemic Toxicity	DG	3	DG	4	DG	3	3
Respiratory Irritation	1	1	2	2	3	DG	3
Aquatic Toxicity	DG	4	DG	DG	DG	DG	3
Persistence	4	3	3	4	3	4	2

Biopolymers	Bad Actor	DG = Data Gap	4 = Low Hazard	3 = Moderate Hazard	2 = High Hazard	1 = Very High Hazard

No Such Thing As a Perfect Polymer



Polymer Blends: **A Promising Solution**



Strategy 1: **Recommended Materials**

	PLA-PCL (80/20)	PHB-PHO (85/15)	LDPE
Degradation Temp (°C)	329 - 358	264	370 - 510
Melting Temp (°C)	170.3	172 - 178	110
Glass Transition Temp (°C)	56.4	DG	-30
Tensile Strength (MPa)	32.8 - 37.6	12 - 16	10 - 15
Elongation at Break (%)	50.5 - 69.1	8 - 11	300 - 500

Home & Industrial Compostability

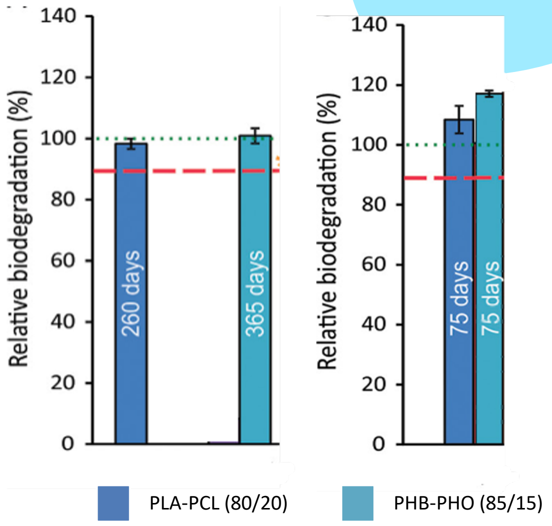


Figure adapted from Narancic T, Verstichel S, Reddy Chaganti S, et al. *Environ Sci Technol*. 2018

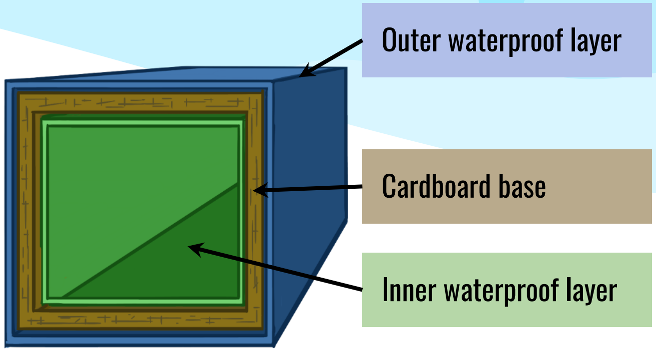
Strategies Overview

Strategy 1

Bioplastics to replace traditional plastics

Strategy 2

Bioplastic coating/laminate attached to structural material



Strategy 3

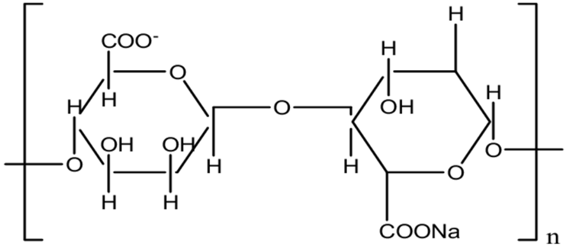
Separate inner bioplastic bag with an outer sturdy structural container

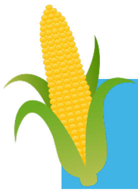
Materials

Alginate

Structural polysaccharides from marine algae

Great at forming films



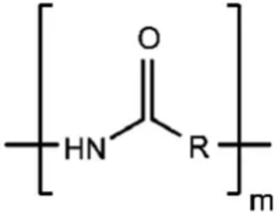


Zein

Plant-based protein

Derived from corn

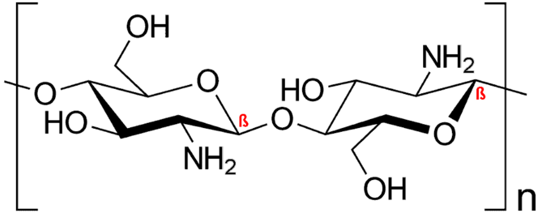
Corn allergies




Chitosan

Made from Chitin, 2nd most abundant polysaccharide

From **shellfish waste or fungi**



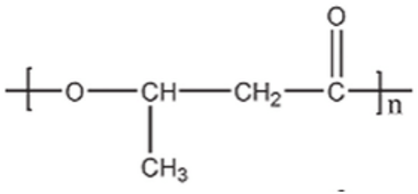
Images from: https://key0.cc/images/preview/168131_05353ecea5c715abf4b768a8200222ef.png, https://key0.cc/freepng/download/83648_Sweet-Corn-Drawing-At-Corn-Clipart,

Materials

PHA

PHB: Short-chain PHA

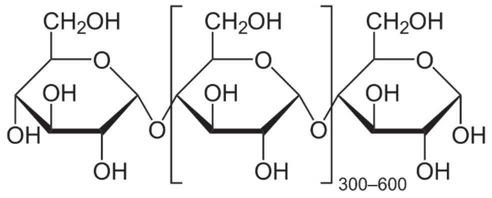
Produced by **bacteria**



Starch

Composed of amylose and amylopectin

Feedstock is food



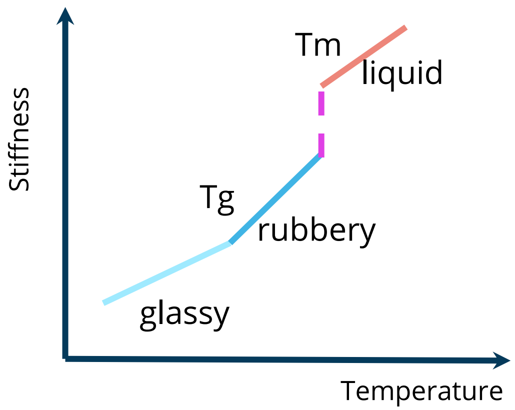
Technical performance: **Barrier properties**

	O_2 permeability ($g/m^2/24$ hrs)	H_2O permeability ($g/m^2/24$ hrs)	Cobb60 (g/m^2)	Kit value
Chitosan	low	high	25 to 50	12
Starch	Very low	Very high	38	7.5
Alginate	low	high	54 to 149	7 to 12
Zein	low	Low with additives	3.1	12
PHA (PHB)	13.4	2.4	DG	DG
LDPE	19.2	0.037	30	12

Technical performance: **Working Temperature Range**

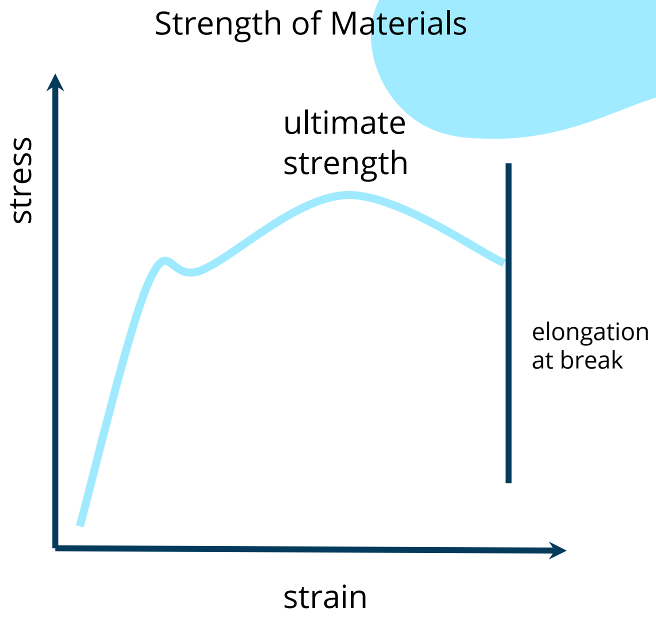
	Degradation (°C)	Melting (°C)	Glass transition (°C)
Chitosan	>250	88	140 - 150
Starch	250 - 350	149 - 155	36
Alginate	250	220	81
Zein	270 - 415	94	139
PHA (PHB)	220	180	4
LDPE	370 - 510	110	-30

Phase Changes with Temperature



Technical performance: **Mechanical Properties**

	Tensile strength (MPa)	Elongation at break (%)
Chitosan	22.2 - 39.6	13 - 73.6
Starch	poor	2
Alginate	12.99 - 21.71	4.94 - 5.14
Zein	7.1 - 7.7	7
PHA (PHB)	40	3 - 6
LDPE	10 - 15	300 - 500



Technical performance: **Mechanical Properties**

	Tensile strength (MPa)	Elongation at break (%)
Chitosan	22.2 - 39.6	13 - 73.6
Starch	poor	2
Alginate	12.99 - 21.71	4.94 - 5.14
Zein	7.1 - 7.7	7
PHA (PHB)	40	3 - 6
LDPE	10 - 15	300 - 500

None of the biopolymers are very flexible

Can stretch it 5x its original length before it breaks

Strategy 2: **Health and Environmental Performance**

	Home Compostable	Industrially Compostable
★ PHA (PHB)	Y	Y
★ Starch	Y	Y
★ Chitosan	Y	Y
★ Alginate	Y	Y
★ Zein	Y	Y
HDPE/LDPE	N	N

Strategy 2: **Health and Environmental Performance**

	PHA (PHB)	PLA	Cellulose	Starch	Chitosan	Alginate	Zein	Polyethylene
Carcinogenicity	4	4	DG	4	DG	4	DG	3
Endocrine Activity	DG	4	DG	DG	DG	DG	DG	DG
Systemic Toxicity	DG	3	DG	3	4	4	DG	3
Respiratory Irritation	1	1	2	3	3	DG	2	3
Aquatic Toxicity	DG	4	DG	4	2	DG	DG	3
Persistence	4	4	4	4	4	4	DG	2

Biopolymers	Bad Actor	DG = Data Gap	4 = Low Hazard	3 = Moderate Hazard	2 = High Hazard	1 = Very High Hazard

Strategy 2: **Recommended Materials**

Chitosan/Zein and Chipboard

- Chitosan has been applied over paper products to largely improve barrier properties with enough coating weight
- Low O_2 and CO_2 permeability
  - Can be improved by addition of bio-additives such as essential oils and/or glycerine
- Has been sourced from seafood waste which helps minimize environmental strain of manufacturing
- Chipboard is biodegradable and verified to be commonly used in food packaging

Strategies Overview

Strategy 1

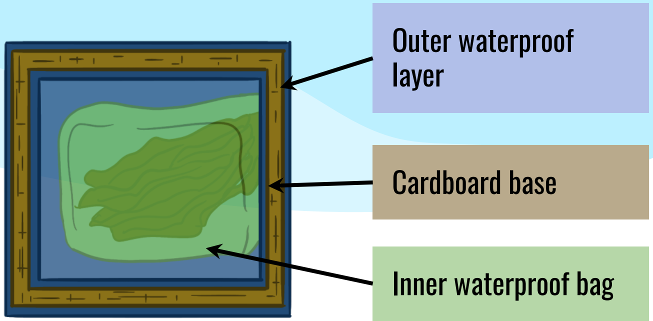
Bioplastics to replace traditional plastics

Strategy 2

Bioplastic coating/laminate attached to structural material

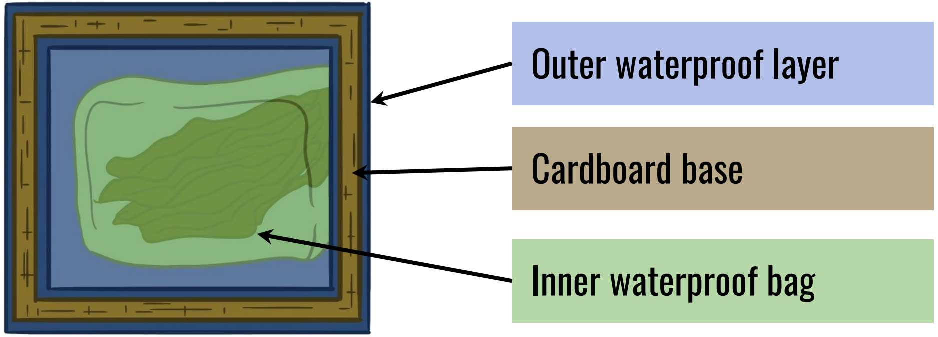
Strategy 3

Separate inner bioplastic bag with an outer sturdy structural container



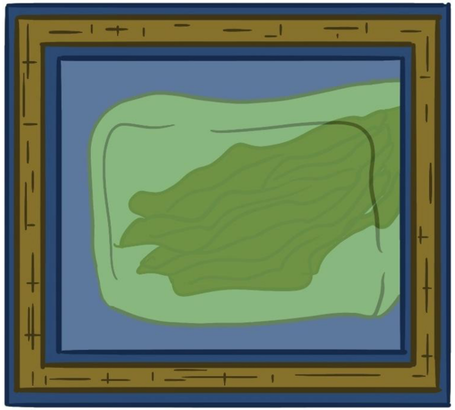
Strategy 1 + Strategy 2 = Strategy 3

- We suggested **PLA/PCL for strategy 1** and **Chitosan/Zein for strategy 2**, but these are not as good as petroleum plastic standards, even if they are compostable.
- Let's look back and combine some materials we had noted were great
  - For strategy 1, what had the best moisture barrier?
  - For strategy 2, what had the best structural parameters? What was the strongest even if it wasn't the most flexible?
- What if we combine Strategies 1 and 2 to make a new packaging strategy?



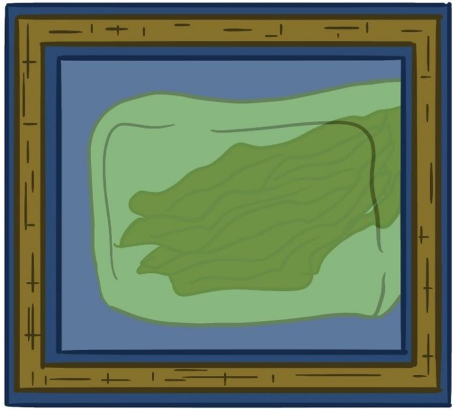
Technical performance: **Barrier Properties** Internal

	O_2 permeability (g/m²/24 hrs)	H_2O permeability (g/m²/24 hrs)
★ PHA (PHB)	13.4	2.4
PLA	3.5-15 cm^3•mm/m^2 day atm	12.6
TPS	3.53×10−5– 1.69×10−1 g•mm•m−2 h−1•kPa−1	0.34–0.65 g•mm•m^{-2} h^{-1}•kPa^{-1}
LDPE	19.2	0.037



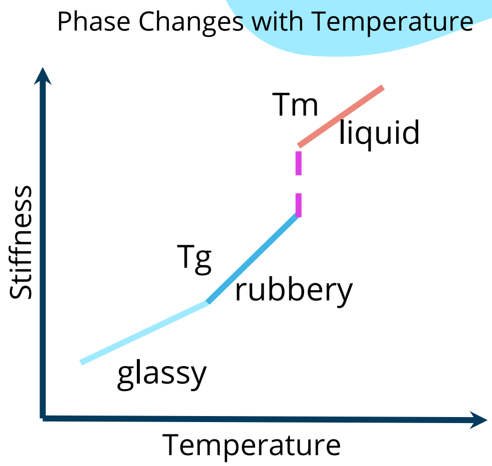
Technical performance: **Barrier properties External**

	O_2 permeability ($g/m^2/24$ hrs)	H_2O permeability ($g/m^2/24$ hrs)	Cobb60 (g/m^2)	Kit value
Chitosan	low	high	25 to 50	12
Starch	Very low	Very high	38	7.5
Alginate	low	high	54 to 149	7 to 12
Zein	low	Low with additives	3.1	12
PHA (PHB)	13.4	2.4	DG	DG
LDPE	19.2	0.037	30	12



Technical performance: **Working Temperature Range**

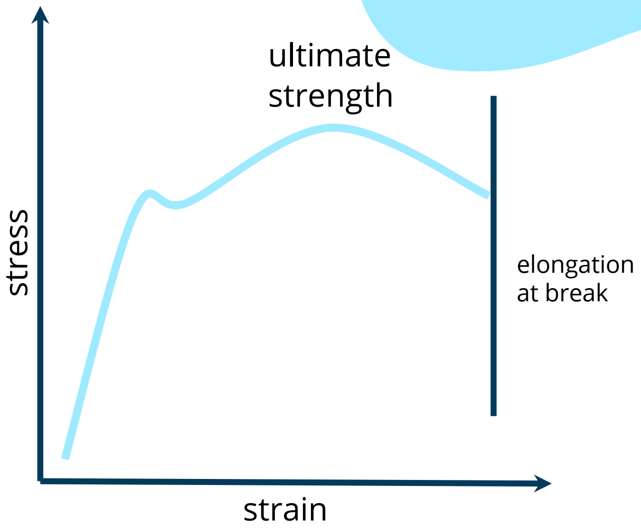
	degradation (°C)	melting (°C)	glass transition (°C)
Chitosan	>250	88	140 - 150
Starch	250 - 350	149 - 155	36
Alginate	250	220	81
Zein	270 - 415	94	139
PHA (PHB)	220	180	4
PLA-PCL (80/20)	329 - 358	170.3	56.4
PHB-PHO (85/15)	264	172 - 178	DG
LDPE	370 - 510	110	-30



Technical performance: **Mechanical properties**

	Tensile Strength (MPa)	Elongation at Break (%)
PBS	28-31	14.6
TPS	6	60
Chitosan	22.2 - 39.6	13 - 73.6
Alginate	12.99 - 21.71	4.94 - 5.14
Zein	7.1 - 7.7	7
PHA (PHB)	40	4.3
PLA-PCL (80/20)	32.8 - 37.6	50.5 - 69.1
PHB-PHO (85/15)	8 - 11	12 - 16
LDPE	10 - 15	300 - 500

Strength of Materials

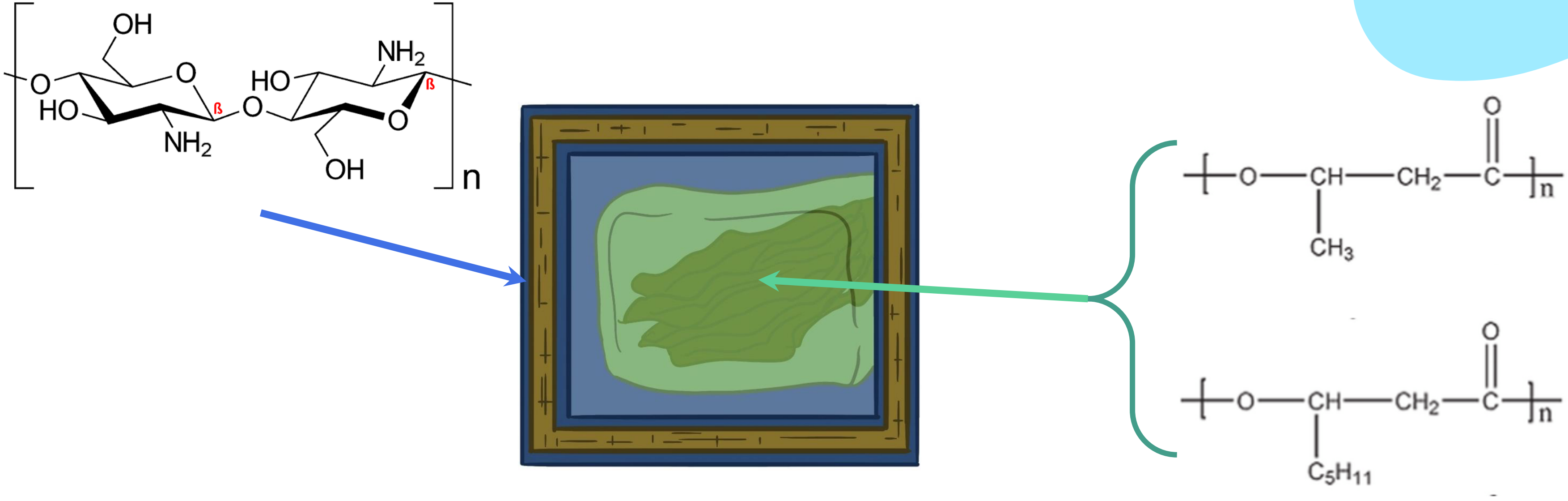


Strategy 3: **Health and Environmental Performance**

	Home Compostable	Industrially Compostable
PHA (PHB)	Y	Y
TPS	Y	Y
Cellulose	Y	Y
Starch	Y	Y
Chitosan	Y	Y
Alginate	Y	Y
Zein	Y	Y

Strategy 3: **Recommended Materials**

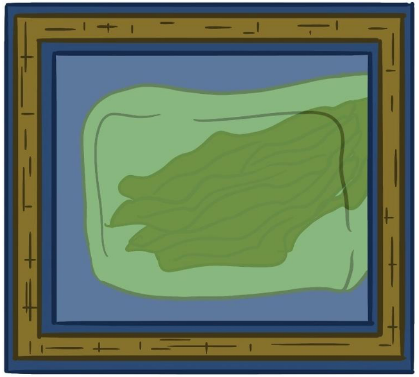
Chitosan on chipboard/PHB-PHO (85/15) blend



Strategy 3: **Recommended Materials**

Chitosan on chipboard/PHB-PHO (85/15) blend

- **Barrier properties:** PHB-PHO has good moisture barrier properties. Chitsan and PHB-PHO have good oxygen barrier properties
- **Working temperature range:** Neither have glass transition temperatures at freezer temperatures but that is not as important because the packaging can be brittle when there are multiple layers and a structural base (chipboard)
- **Mechanical properties:** Chitosan was the best mechanical properties of all the laminate/coating materials
- **Compostability:** All materials are home compostable



Recommended Strategies

Strategy 1	Strategy 2	Strategy 3
PLA/PCL bioplastic bag as direct replacement for LDPE bags	Chitosan/Zein mixture as laminate/coating for chipboard box	PHB/PHO bioplastic bag inside chitosan laminated/coated box

Recommended Strategies

	Strategy 1	Strategy 2	Strategy 3
PROS	1. Easier implementation 2. Simple design → less waste 3. Thin bag → faster biodegradation	1. Chitosan & Chipboard from waste 2. Established & scalable manufacturing process 3. Chitosan & Zein compounds have proven enhanced properties	1. Structural material increases possible bioplastics 2. Established & scalable manufacturing process 3. Chitosan & Chipboard from waste 4. Layers improve overall properties
CONS	1. Trades off durability for biodegradability 2. Must use fossil-based additives	1. Must have additives to improve base properties 2. May need thicker inner lamination/coating of bioplastic	1. Multiple components → increased complexity 2. Multiple manufacturing processes → increased cost

Recommended Strategies

Strategy 1

PROS

1. Easier implementation
2. Simple design → less waste
3. Thin bag → faster biodegradation

CONS

1. Trades off durability for biodegradability
2. Must use fossil-based additives

Strategy 2

PROS

1. Chitosan & Chipboard from waste
2. Established & scalable manufacturing process
3. Chitosan & Zein compounds have proven enhanced properties

CONS

1. Must have additives to improve base properties
2. May need thicker inner lamination/coating of bioplastic

Strategy 3 ★

PROS

1. Structural material increases possible bioplastics
2. Established & scalable manufacturing process
3. Chitosan & Chipboard from waste
4. Layers improve overall properties

CONS

1. Multiple components → increased complexity
2. Multiple manufacturing processes → increased cost

Next Steps

1

Now

Mango Materials produces **PHB films**, has partnered with CPG companies (Consumer Packaged Goods) in the past to produce packaging

Full Cycle bioplastics also does **PHA products**, unsure on films/food packaging

2

Soon

Sway Company: Seaweed-based packaging but still in **developmental stages**

3

Future

Zein/Chitosan films (potentially even edible ones!)

Acknowledgements

We would like to thank the Greener Solutions team (Meg, Billy, Kim), our industry mentor (Ryan), and Noble Ocean Farms (Skye) for guidance throughout the project!

Questions?

CREDITS: This presentation template was created by **Slidesgo**, including icons by **Flaticon**, infographics & images by **Freepik** and illustrations by **Stories**

References

A critical review on production of biopolymers from algae biomass and their applications - ScienceDirect https://www.sciencedirect.com/science/article/pii/S0960852421002078#! (accessed 2021 -09 -14).

Jian, J.; Xiangbin, Z.; Xianbo, H. An Overview on Synthesis, Properties and Applications of Poly(Butylene-Adipate-Co-Terephthalate)–PBAT. *Advanced Industrial and Engineering Polymer Research* **2020**, *3* (1), 19–26. https://doi.org/10.1016/j.aiepr.2020.01.001

Kopacic, S.; Walzl, A.; Hirn, U.; Zankel, A.; Kniely, R.; Leitner, E.; Bauer, W. Application of Industrially Produced Chitosan in the Surface Treatment of Fibre-Based Material: Effect of Drying Method and Number of Coating Layers on Mechanical and Barrier Properties. *Polymers* **2018**, *10* (11), 1232. https://doi.org/10.3390/polym10111232.

Rhim, J.-W.; Park, H.-M.; Ha, C.-S. Bio-Nanocomposites for Food Packaging Applications. *Progress in Polymer Science* **2013**, *38* (10), 1629–1652. https://doi.org/10.1016/j.progpolymsci.2013.05.008.

Abdel Aziz, M. S.; Salama, H. E.; Sabaa, M. W. Biobased Alginate/Castor Oil Edible Films for Active Food Packaging. *LWT* **2018**, *96*, 455–460. https://doi.org/10.1016/j.lwt.2018.05.049.

Narancic, T.; Verstichel, S.; Reddy Chaganti, S.; Morales-Gamez, L.; Kenny, S. T.; De Wilde, B.; Babu Padamati, R.; O'Connor, K. E. Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. *Environ. Sci. Technol.* **2018**, *52* (18), 10441–10452. https://doi.org/10.1021/acs.est.8b02963.

Serna, C. P.; Filho, J. F. L. Biodegradable Zein-Based Blend Films: Structural, Mechanical and Barrier Properties. *Food Technol Biotechnol* **2015**, *53* (3), 348–353. https://doi.org/10.17113/ftb.53.03.15.3725.

References

Cereplast Expands Bioplastic Applications with Freeze-Tolerant Compostable Resin https://materialdistrict.com/article/cereplast-expands-bioplastic-applications-with-freeze-tolerant-compostable-resin/ (accessed 2021 -09 -14).

Rodriguez-Perez, S.; Serrano, A.; Pantión, A. A.; Alonso-Fariñas, B. Challenges of Scaling-up PHA Production from Waste Streams. A Review. *Journal of Environmental Management* **2018**, *205*, 215–230. https://doi.org/10.1016/j.jenvman.2017.09.083.

Yoshida, C. M. P.; Oliveira Junior, E. N.; Franco, T. T. Chitosan Tailor-Made Films: The Effects of Additives on Barrier and Mechanical Properties. *Packaging Technology and Science* **2009**, *22* (3), 161–170. https://doi.org/10.1002/pts.839.

Composting PLA Plastic at Home - Green SXM http://greensxm.com/composting-pla-plastic/ (accessed 2021 -11 -16).

Müller, C. M. O.; Laurindo, J. B.; Yamashita, F. Effect of Cellulose Fibers on the Crystallinity and Mechanical Properties of Starch-Based Films at Different Relative Humidity Values. *Carbohydrate Polymers* **2009**, *77* (2), 293–299. https://doi.org/10.1016/j.carbpol.2008.12.030.

Montilla-Buitrago, C. E.; Gómez-López, R. A.; Solanilla-Duque, J. F.; Serna-Cock, L.; Villada-Castillo, H. S. Effect of Plasticizers on Properties, Retrogradation, and Processing of Extrusion-Obtained Thermoplastic Starch: A Review. *Starch - Stärke* **2021**, *73* (9–10), 2100060. https://doi.org/10.1002/star.202100060.

In vitro toxicity of bioplastics and plant-based materials | Food Packaging Forum https://www.foodpackagingforum.org/news/in-vitro-toxicity-of-bioplastics-and-plant-based-materials (accessed 2021 -11 -26).

References

Li, J.; Jinqiang, G.; Sui, G.; Jia, L.; Zuo, C.; Deng, Q. Influence of a Glycerin Additive on the Structure and Water Vapor Permeance of Chitosan Membranes. *Materials Express* **2014**, *4*. https://doi.org/10.1166/mex.2014.1200.

J. Compos. Sci. | Free Full-Text | Study of the Preparation and Properties of TPS/PBSA/PLA Biodegradable Composites https://www.mdpi.com/2504-477X/5/2/48 (accessed 2021 -11 -24).

Mali, S.; Grossmann, M. V. E.; Garcia, M. A.; Martino, M. N.; Zaritzky, N. E. Microstructural Characterization of Yam Starch Films. *Carbohydrate Polymers* **2002**, *50* (4), 379–386. https://doi.org/10.1016/S0144-8617(02)00058-9.

Deng, Y.; Yu, C.; Wongwiwattana, P.; Thomas, N. L. Optimising Ductility of Poly(Lactic Acid)/Poly(Butylene Adipate-Co-Terephthalate) Blends Through Co-Continuous Phase Morphology. *J Polym Environ* **2018**, *26* (9), 3802–3816. https://doi.org/10.1007/s10924-018-1256-x.

PBS https://polymerdatabase.com/Polymer%20Brands/PBS.html (accessed 2021 -11 -10).

PET vs. PLA :: MakeItFrom.com https://www.makeitfrom.com/compare/Polyethylene-Terephthalate-PET-PETE/Polylactic-Acid-PLA-Polylactide (accessed 2021 -11 -10).

Bocqué, M.; Voirin, C.; Lapinte, V.; Caillol, S.; Robin, J.-J. Petro-Based and Bio-Based Plasticizers: Chemical Structures to Plasticizing Properties. *Journal of Polymer Science Part A: Polymer Chemistry* **2016**, *54* (1), 11–33. https://doi.org/10.1002/pola.27917.

Hoeven, D. van der. PHA: promising, versatile, biodegradable https://www.biobasedpress.eu/2016/08/pha-promising-versatile-biodegradable/ (accessed 2021 -11 -17).

References

Zhou, L.; Wang, Y. Physical and Antimicrobial Properties of Zein and Methyl Cellulose Composite Films with Plasticizers of Oleic Acid and Polyethylene Glycol. *LWT* **2021**, *140*, 110811. https://doi.org/10.1016/j.lwt.2020.110811.

Escamilla-García, M.; Calderón-Domínguez, G.; Chanona-Pérez, J. J.; Farrera-Rebollo, R. R.; Andraca-Adame, J. A.; Arzate-Vázquez, I.; Mendez-Mendez, J. V.; Moreno-Ruiz, L. A. Physical and Structural Characterisation of Zein and Chitosan Edible Films Using Nanotechnology Tools. *International Journal of Biological Macromolecules* **2013**, *61*, 196–203. https://doi.org/10.1016/j.ijbiomac.2013.06.051.

Arvanitoyannis, I.; Biliaderis, C. G. Physical Properties of Polyol-Plasticized Edible Blends Made of Methyl Cellulose and Soluble Starch. *Carbohydrate Polymers* **1999**, *38* (1), 47–58. https://doi.org/10.1016/S0144-8617(98)00087-3.

Escamilla-García, M.; Calderón-Domínguez, G.; Chanona-Pérez, J.; Mendoza-Madrigal, A.; Di Pierro, P.; García-Almendárez, B.; Amaro-Reyes, A.; Regalado-González, C. Physical, Structural, Barrier, and Antifungal Characterization of Chitosan–Zein Edible Films with Added Essential Oils. *IJMS* **2017**, *18* (11), 2370. https://doi.org/10.3390/ijms18112370.

Manek, R. V.; Kunle, O. O.; Emeje, M. O.; Builders, P.; Rao, G. V. R.; Lopez, G. P.; Kolling, W. M. Physical, Thermal and Sorption Profile of Starch Obtained from Tacca Leontopetaloides. *Starch - Stärke* **2005**, *57* (2), 55–61. https://doi.org/10.1002/star.200400341.

Plastic made from biomass logs the highest heat resistance on record https://newatlas.com/materials/plastic-biomass-highest-heat-resistance-record/ (accessed 2021 -09 -14).

References

US EPA, O. Plastics: Material-Specific Data https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (accessed 2021 -09 -19).

Wang, L.; Zhang, M.; Lawson, T.; Kanwal, A.; Miao, Z. Poly(Butylene Succinate-Co-Salicylic Acid) Copolymers and Their Effect on Promoting Plant Growth. *Royal Society Oper Science 6* (7), 190504. https://doi.org/10.1098/rsos.190504.

Polymers | Free Full-Text | Poly(butylene succinate) Ionomers with Enhanced Hydrodegradability https://www.mdpi.com/2073-4360/7/7/1232 (accessed 2021 -11 -26).

Preparation of Corn Zein Based Biodegradable Resin...(T99030) | UIUC Office of Technology Management https://otm.illinois.edu/technologies/preparation-corn-zein-based-biodegradable-resint99030 (accessed 2021 -11 -23).

Cuevas-Carballo, Z. B.; Duarte-Aranda, S.; Canché-Escamilla, G. Properties and Biodegradability of Thermoplastic Starch Obtained from Granular Starches Grafted with Polycaprolactone. *International Journal of Polymer Science* **2017**, *2017*, e3975692. https://doi.org/10.1155/2017/3975692.

Properties of Biodegradable Films Based on Poly(butylene Succinate) (PBS) and Poly(butylene Adipate-co-Terephthalate) (PBAT) Blends † https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7600530/ (accessed 2021 -11 -24).

Recent advances in gelatine and chitosan complex material for practical food preservation application - Wang - 2021 - International Journal of Food Science & Technology - Wiley Online Library https://ifst.onlinelibrary.wiley.com/doi/full/10.1111/ijfs.15340 (accessed 2021 -11 -18).

SEABIOPLAS Producing Plastic Sustainably from Farmed Seaweed https://thefishsite.com/articles/seabioplas-producing-plastic-sustainably-from-farmed-seaweed (accessed 2021 -09 -14).

References

Photopoulos, J.; Magazine, F. H.; Research, H. T. E.; Magazine, I. Seaweed coffee cups could help ditch single-use plastics https://phys.org/news/2018-10-seaweed-coffee-cups-ditch-single-use.html (accessed 2021 -09 -14).

Siddaramaiah; Swamy, T. M. M.; Ramaraj, B.; Lee, J. H. Sodium Alginate and Its Blends with Starch: Thermal and Morphological Properties. *Journal of Applied Polymer Science* **2008**, *109* (6), 4075–4081. https://doi.org/10.1002/app.28625.

Study finds bioplastics to be just as toxic as regular plastic https://newatlas.com/materials/study-bioplastics-toxic-regular-plastic/?itm_source=newatlas&itm_medium=article-body (accessed 2021 -09 -14).

Wang, Y.; Zhong, Y.; Shi, Q.; Guo, S. Study of the Preparation and Properties of TPS/PBSA/PLA Biodegradable Composites. *Journal of Composites Science* **2021**, *5* (2), 48. https://doi.org/10.3390/jcs5020048.

PubChem. Succinic acid https://pubchem.ncbi.nlm.nih.gov/compound/1110 (accessed 2021 -11 -26).

Sustainable innovation – the rise of seaweed-based bioplastics in Europe https://www.innovationnewsnetwork.com/sustainable-innovation-the-rise-of-seaweed-based-bioplastics-in-europe/6513/ (accessed 2021 -09 -14).

Pérez-Pacheco, E.; Canto-Pinto, J. C.; Manuel Moo-Huchin, V.; Estrada-Mota, I. A.; Chel-Guerrero, R. J. E.-L. and L. *Thermoplastic Starch (TPS)-Cellulosic Fibers Composites: Mechanical Properties and Water Vapor Barrier: A Review*; IntechOpen, 2016. https://doi.org/10.5772/65397.

References

Zhang, Y.; Rempel, C.; Liu, Q. Thermoplastic Starch Processing and Characteristics—A Review. *Critical Reviews in Food Science and Nutrition* **2014**, *54* (10), 1353–1370. https://doi.org/10.1080/10408398.2011.636156.

Anbukarasu, P.; Sauvageau, D.; Elias, A. Tuning the Properties of Polyhydroxybutyrate Films Using Acetic Acid via Solvent Casting. *Sci Rep* **2015**, *5*, 17884. https://doi.org/10.1038/srep17884.

Nag, A.; Ali, M. A.; Kawaguchi, H.; Saito, S.; Kawasaki, Y.; Miyazaki, S.; Kawamoto, H.; Adi, D. T. N.; Yoshihara, K.; Masuo, S.; Katsuyama, Y.; Kondo, A.; Ogino, C.; Takaya, N.; Kaneko, T.; Ohnishi, Y. Ultrahigh Thermoresistant Lightweight Bioplastics Developed from Fermentation Products of Cellulosic Feedstock. *Advanced Sustainable Systems* **2021**, *5* (1), 2000193. https://doi.org/10.1002/adsu.202000193.

Mali, S.; Sakanaka, L. S.; Yamashita, F.; Grossmann, M. V. E. Water Sorption and Mechanical Properties of Cassava Starch Films and Their Relation to Plasticizing Effect. *Carbohydrate Polymers* **2005**, *60* (3), 283–289. https://doi.org/10.1016/j.carbpol.2005.01.003.

Robertson, N. What Are Bioplastics? https://www.cereplast.com/bioplastics/ (accessed 2021 -09 -14).

Narancic T, Verstichel S, Reddy Chaganti S, et al. Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. Environ Sci Technol. 2018;52(18):10441-10452. doi:10.1021/acs.est.8b02963
nova-Institute (Germany), OWS (Belgium), Hydra Marine Science (Italy/Germany), IKT Stuttgart (Germany) in cooperation with DIN CERTCO and TÜV Austria. Biodegradable Polymers in Various Environments According to Established Standards and Certification Schemes – Graphic (PDF).; 2021.

Narancic, T.; Verstichel, S.; Chaganti, S. R.; Morales-Gamez, L.; Kenny, S. T.; Wilde, B. D.; Padamati, R. B.; O'Connor, K. E. Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. Environmental Science & Technology 2018.

References

Nerkar, M.; Ramsay, J. A.; Ramsay, B. A.; Kontopoulou, M. Melt Compounded Blends of Short and Medium Chain-Length Poly-3-Hydroxyalkanoates. J Polym Environ 2014, 22 (2), 236–243. https://doi.org/10.1007/s10924-013-0635-6.

Chen, C.-C.; Chueh, J.-Y.; Tseng, H.; Huang, H.-M.; Lee, S.-Y. Preparation and Characterization of Biodegradable PLA Polymeric Blends. Biomaterials 2003, 24 (7), 1167–1173. https://doi.org/10.1016/S0142-9612(02)00466-0.

Li, Z.; Yang, J.; Loh, X. J. Polyhydroxyalkanoates: Opening Doors for a Sustainable Future. NPG Asia Mater 2016, 8 (4), e265–e265. https://doi.org/10.1038/am.2016.48.

Biobased Polybutylene Succinate (PBS) – An Attractive Polymer for Biopolymer Compounds − Full Version. Succinity GMBH, nova-institute October 2016.

Rastogi VK, Samyn P. Bio-Based Coatings for Paper Applications. *Coatings*. 2015;5(4):887-930. doi:10.3390/coatings5040887

2. Li J, Gao J, Sui G, Jia L, Zuo C, Deng Q. Influence of a glycerin additive on the structure and water vapor permeance of chitosan membranes. *Materials Express*. 2014;4(6):491-498. doi:10.1166/mex.2014.1200