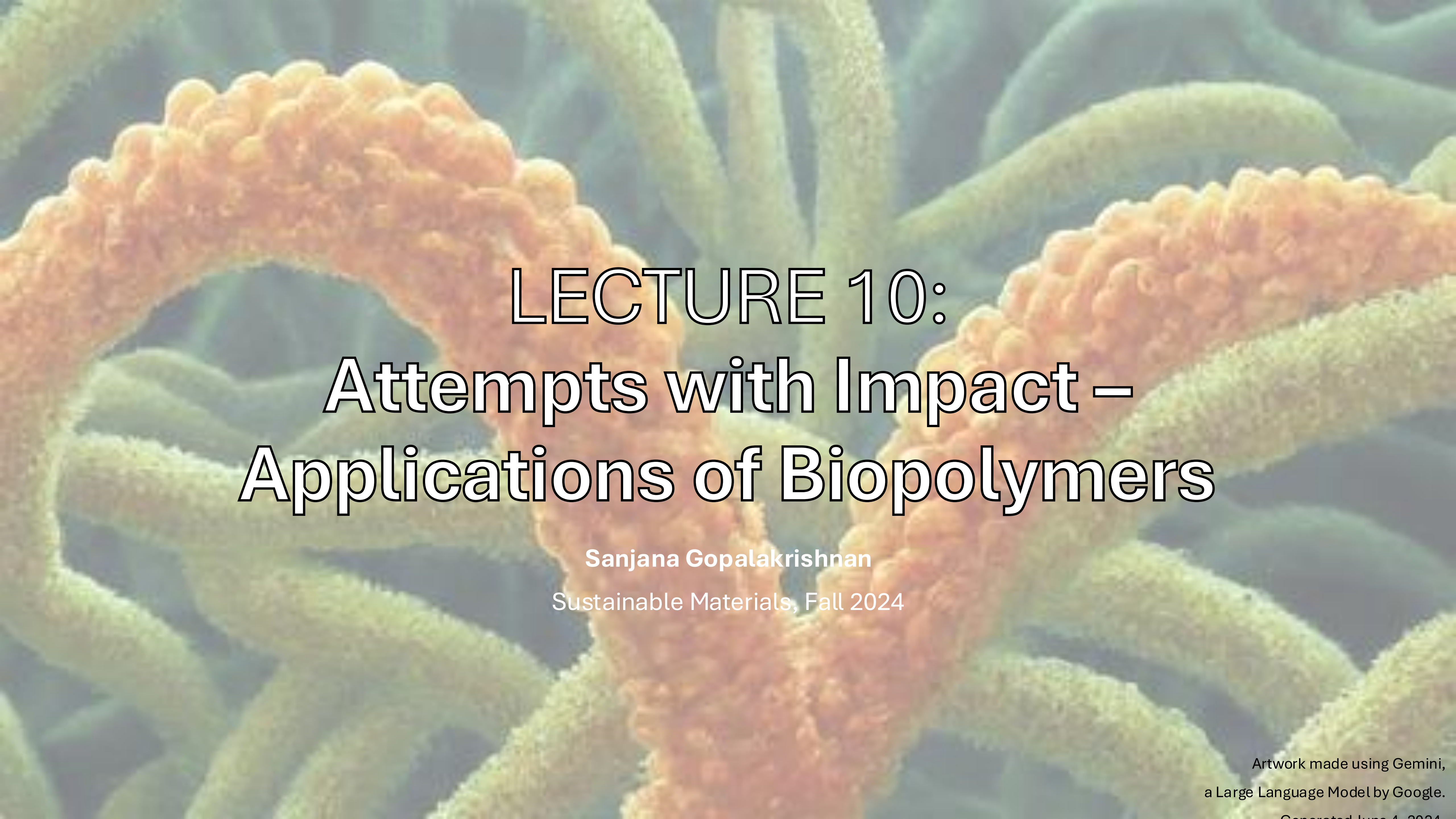

LECTURE 10:
Attempts with Impact – Applications of Biopolymers

Sanjana Gopalakrishnan

Sustainable Materials, Fall 2024

Artwork made using Gemini,
a Large Language Model by Google.
Generated June 4, 2024

Course Overview

Introduction
- Overview
- Historical Perspective

Challenges
- Human Health
- Environment

Solutions
- Old Polymers
- Emerging Concepts
- Attempts w/Impact

Applications
- Food and Ag
- Electronics and Optics
- Healthcare

Future
- What do we need?
- How do we get there?

Lecture 9-10

Introduction

- Overview
- Historical Perspective

Challenges

- Human Health
- Environment

Solutions

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- Attempts w/Impact

Applications

- Food and Ag
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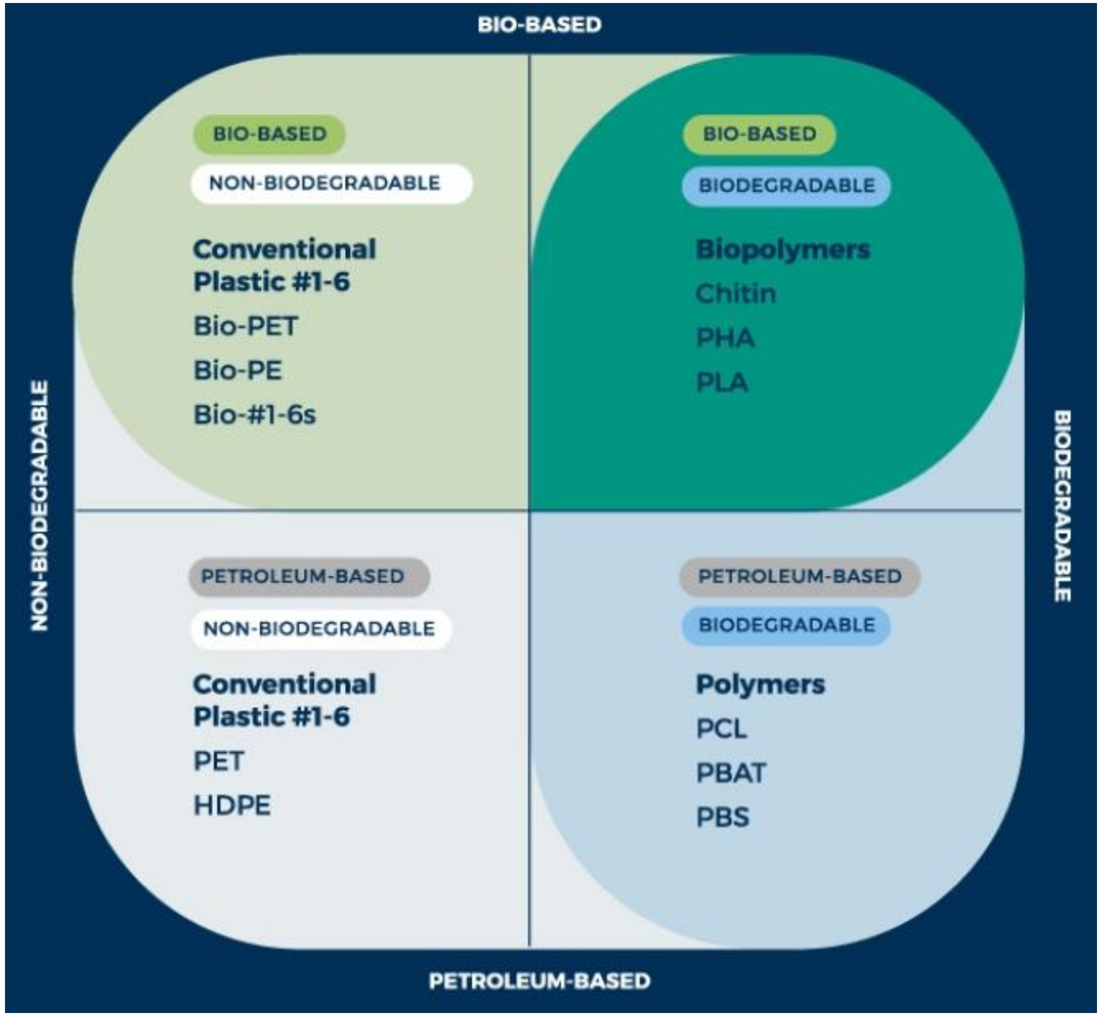
- Healthcare

Future

- What do we need?
- How do we get there?

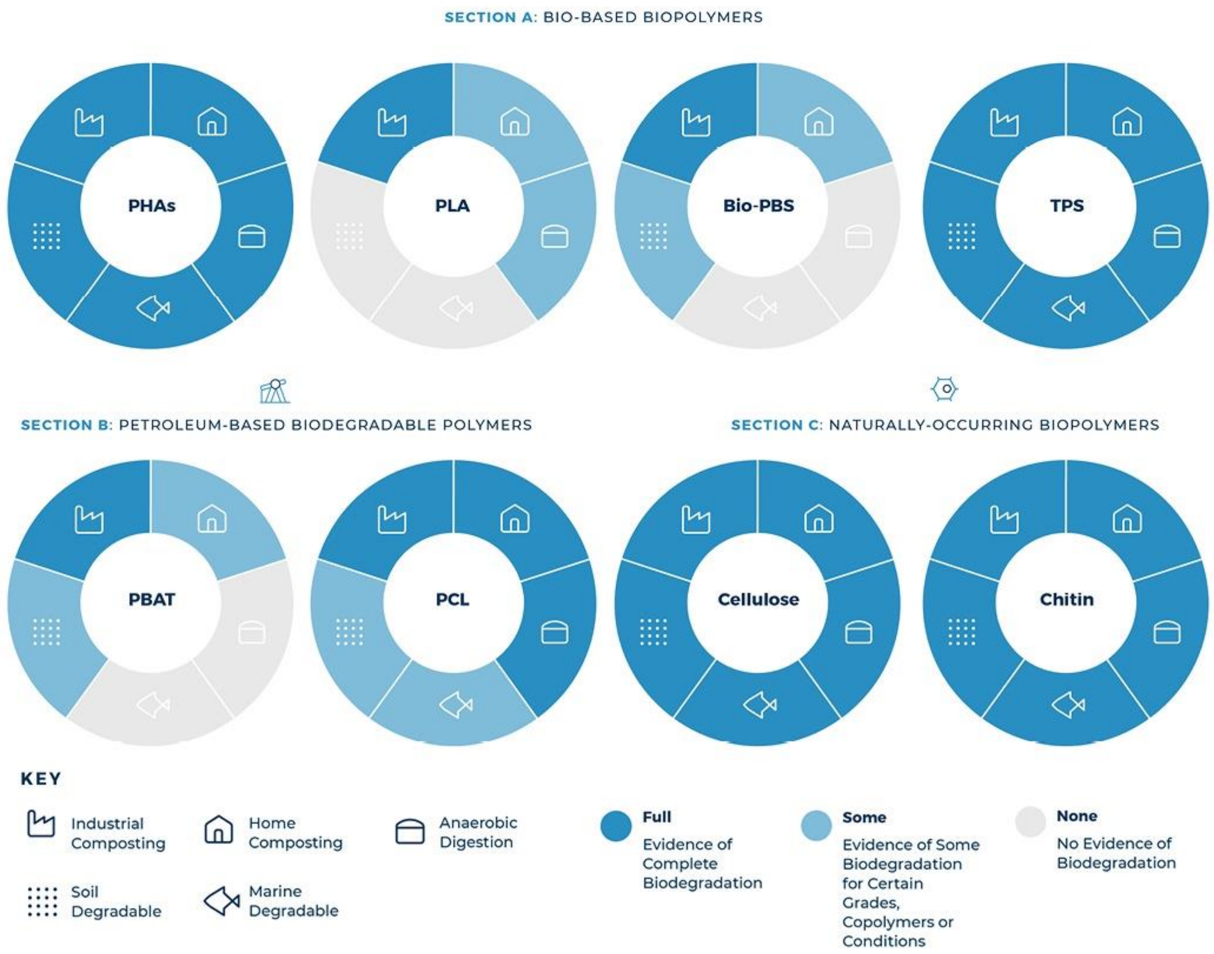
Bio-based Raw Materials as Alternative Feedstock



- Using petroleum-based feedstock to develop biodegradable polymers
- Using bio-based feedstock to develop conventional polymers
- Using bio-based feedstock to develop biodegradable synthetic polymers
- Using bio-based feedstock to extract biopolymers

Source: https://www.biocycle.net/demystifying-biopolymers-and-compostable-packaging/

Biodegradability of Biosynthetic Polymers

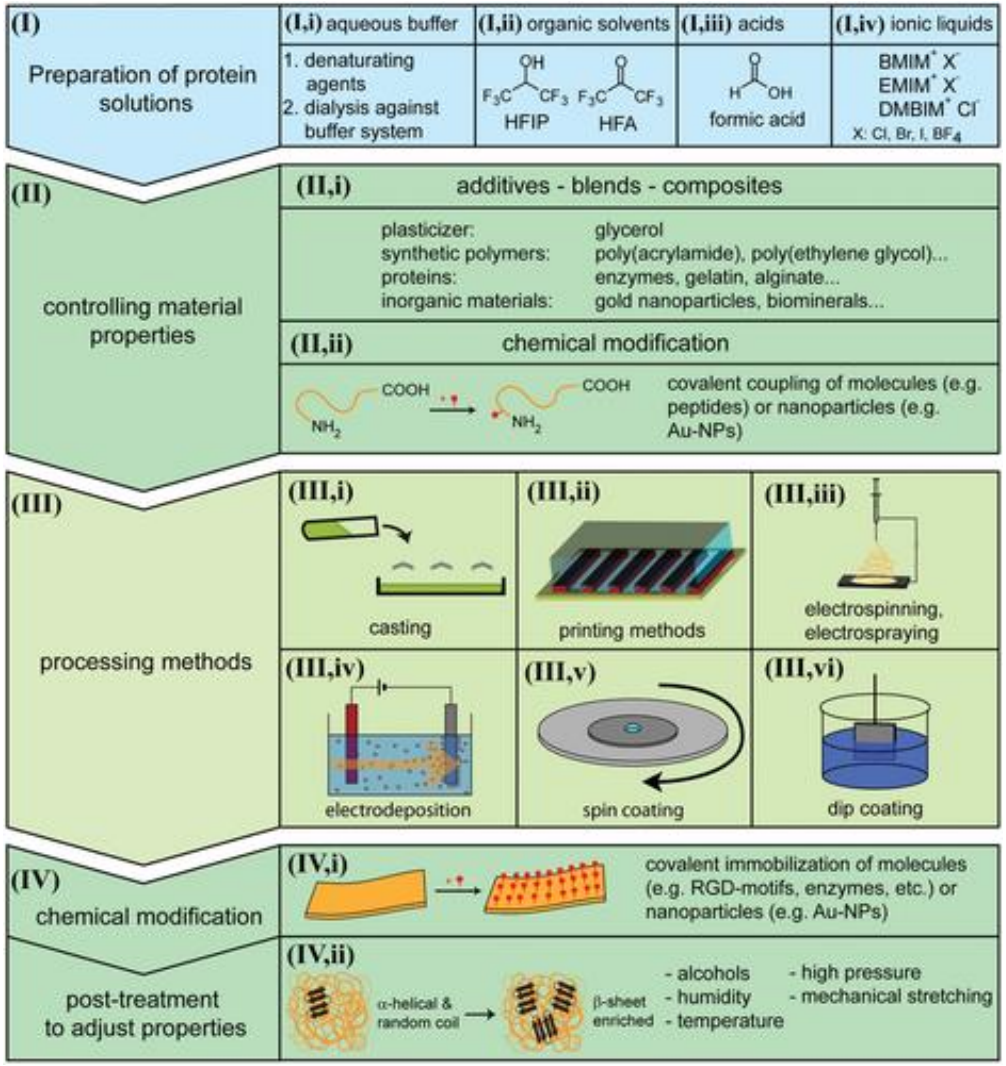


- Environmental factors such as aerobic vs. anerobic degradation should be considered
- Bio-based feedstock is not always the answer – PCL is more easily degradable than PLA
- Polymer molecular weights (grades) additives, copolymers play a big role

Source: https://www.biocycle.net/demystifying-biopolymers-and-compostable-packaging/

Type of Modifications

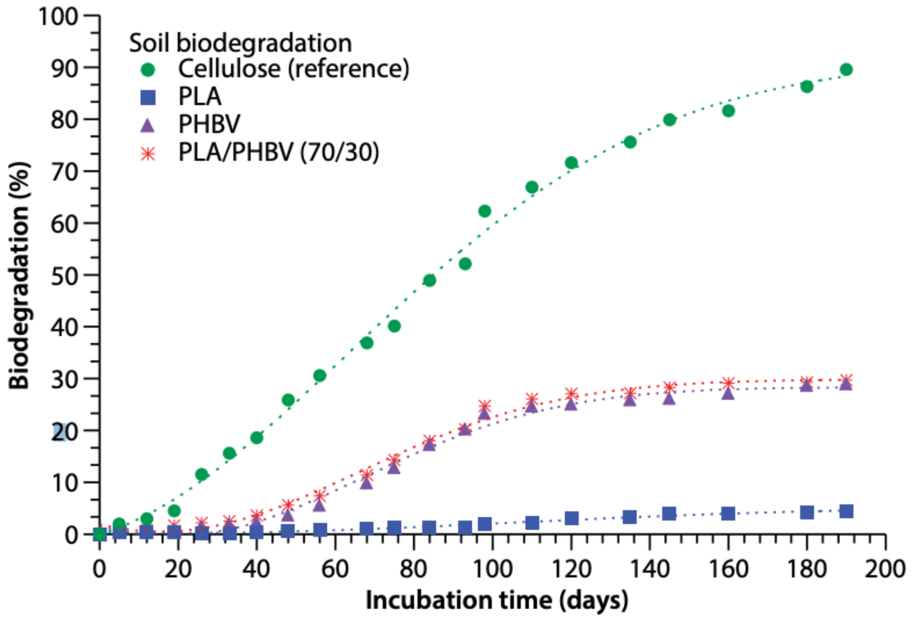
- **Physical:** Altering the secondary and tertiary structure without altering the primary structure
  - Heat, pressure, solvents, pH changes, humidity etc.
- **Chemical:** Introducing new chemical functionalities into the primary structure
  - Crosslinking, grafting
- **Composites/Additives:** Mixing one or more reagents with biopolymers to alter properties
  - Using other biopolymers or plasticizers to alter functionality
- **Fabrication Techniques:** Affects material formats and macro-structure

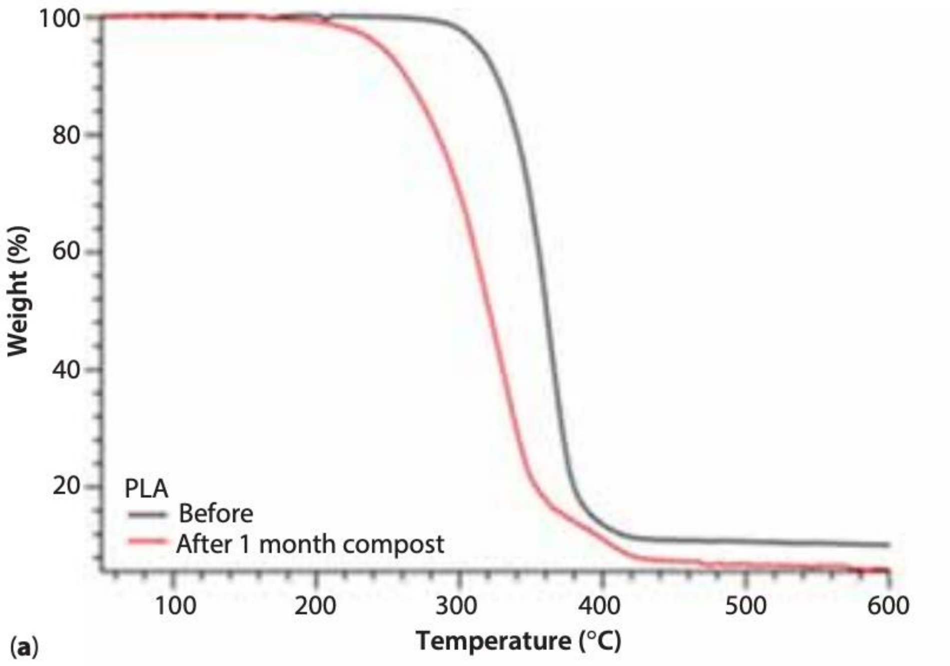


Outline for Today

- Bioplastics
  - Solving the PLA problem – enzyme encapsulation
  - Flax-based elastomers
  - Silk-based thermoplastics
- Films and Coatings
  - Food packaging materials
  - Hydrophobic coatings- Alternatives to Teflon
  - Biopolymer –based filtration
- Bio-based Materials
  -
- Additives
  - Adhesives
  - Silicone Elastomer Alternatives

The PLA Problem: Not Actually Compostable





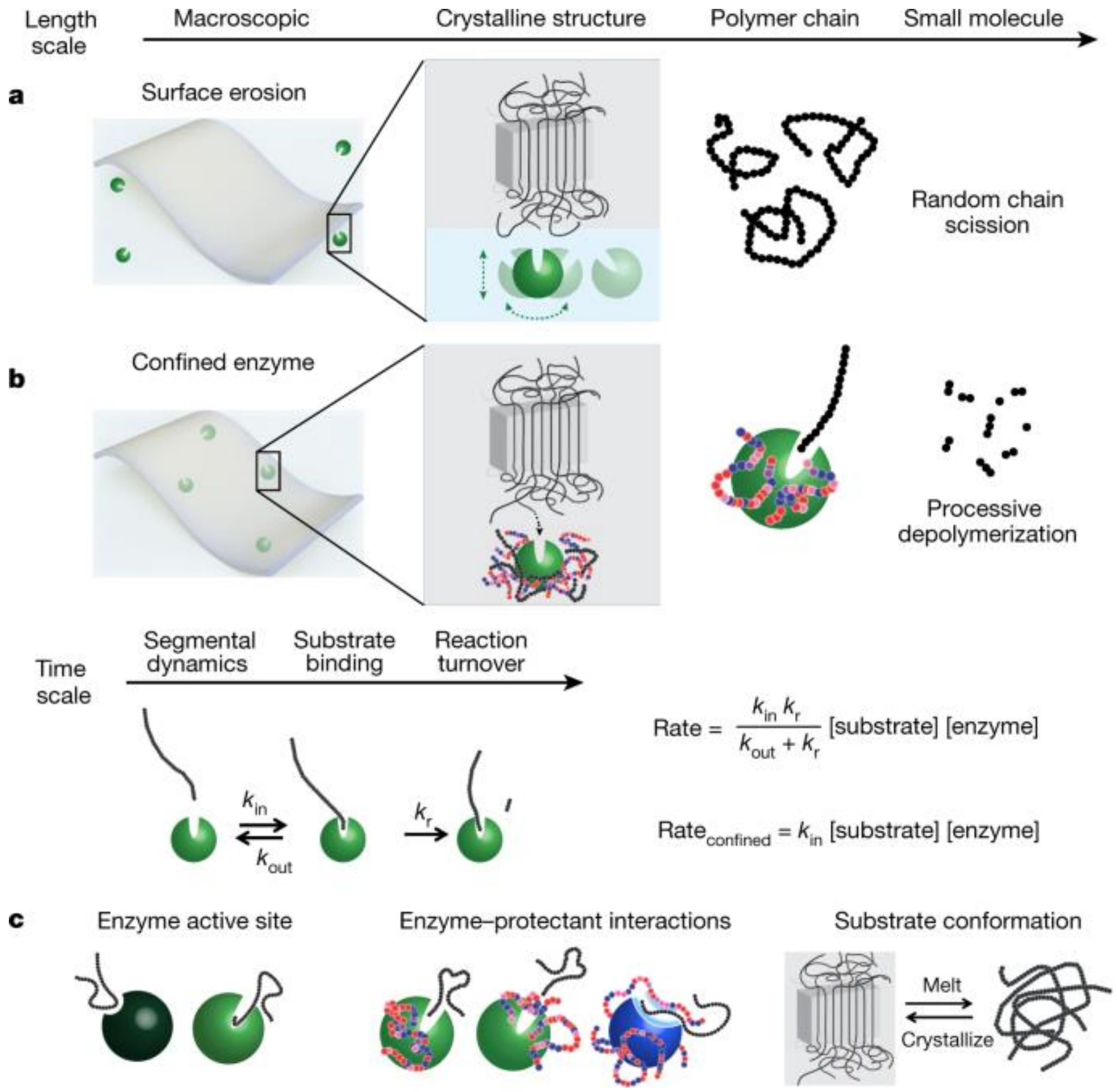
- PLA does not biodegrade in soil
- Thermal stability (TGA) of PLA after 1 month of composting has minimal change
- Degradation requires specific temperatures (55-75 °C) and anerobic conditions

Solving the PLA Problem

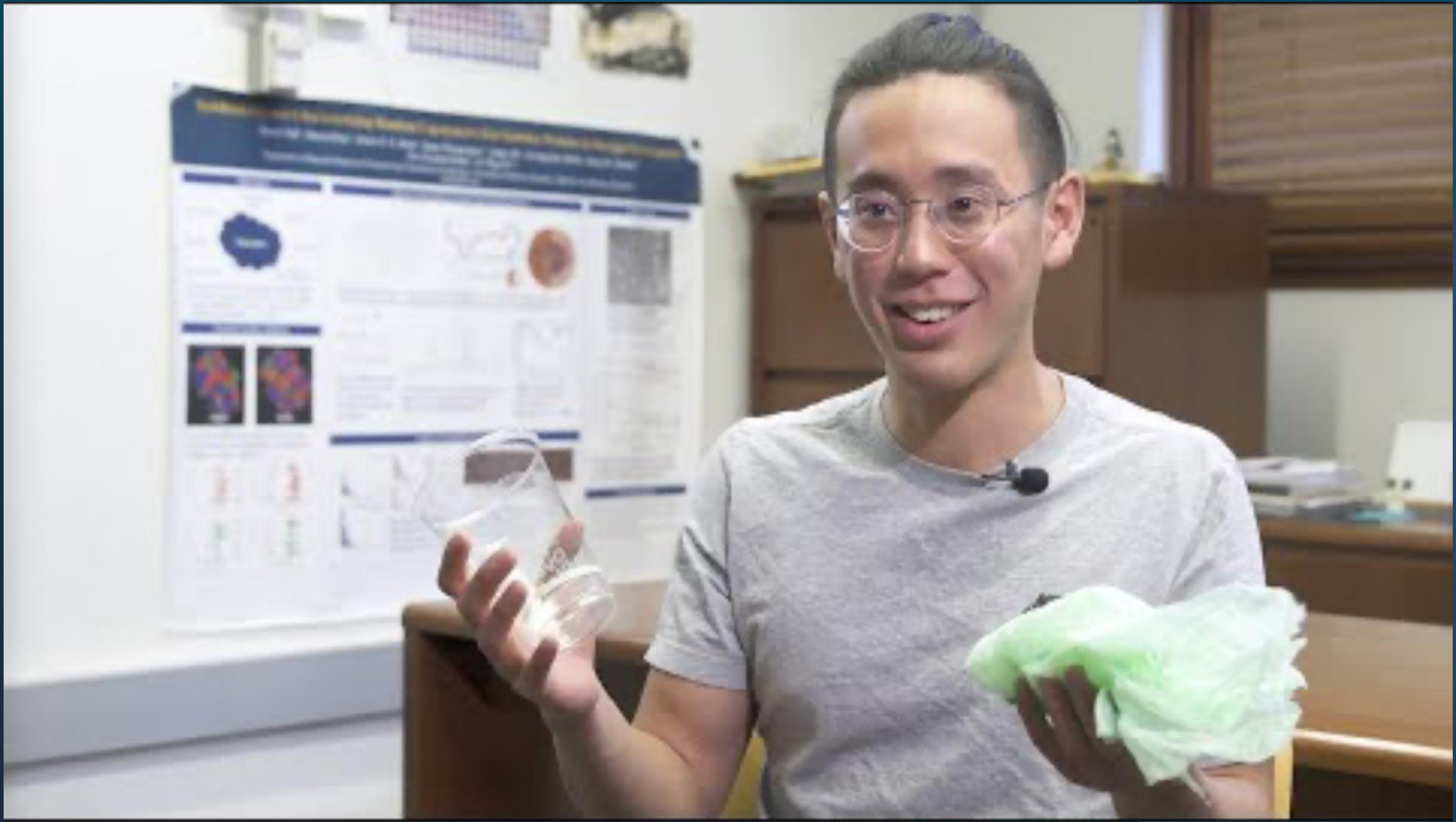
- **Integration of Enzymes:** Formulating PLA plastics with embedded enzymes for improved biodegradation
- **Biopolymer Composites:** Compositing with a biopolymer to enhance breakdown during composting

Enzyme additive into Bio-synthetic Plastics

- Enzymes are confined within the bio-synthetic plastic prior to fabrication
- Enzyme is surrounded by a protectant matrix that preserves activity throughout plastic processing including in organic solvent
- Protectant-enzyme interactions facilitate processive depolymerization

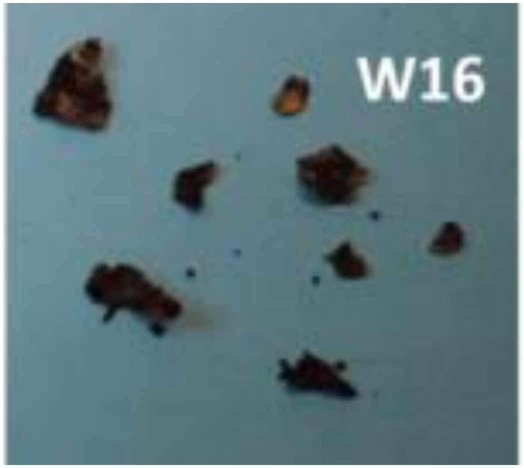


DelRe, C. et al *Nature* **2021**



CARBIOS: Enzyme-loaded PLA Single-use Plastics

- 5% Carbios active enzyme encapsulated in PLA films for degradation testing
- Disintegration in 2-6 weeks. Total biodegradation in 120 days (microplastics)
- No toxicity observed

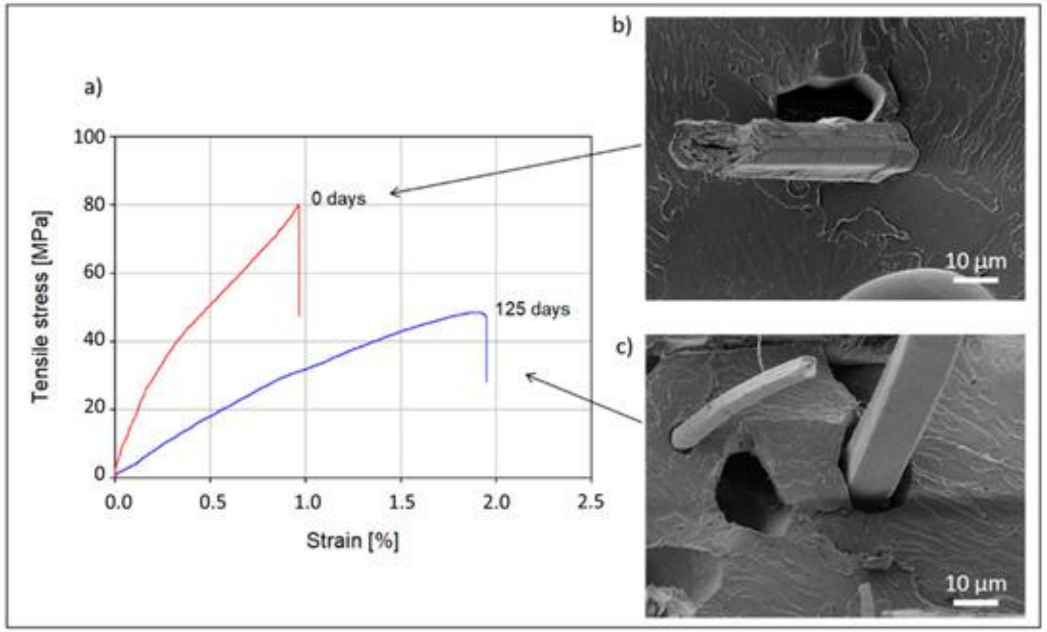


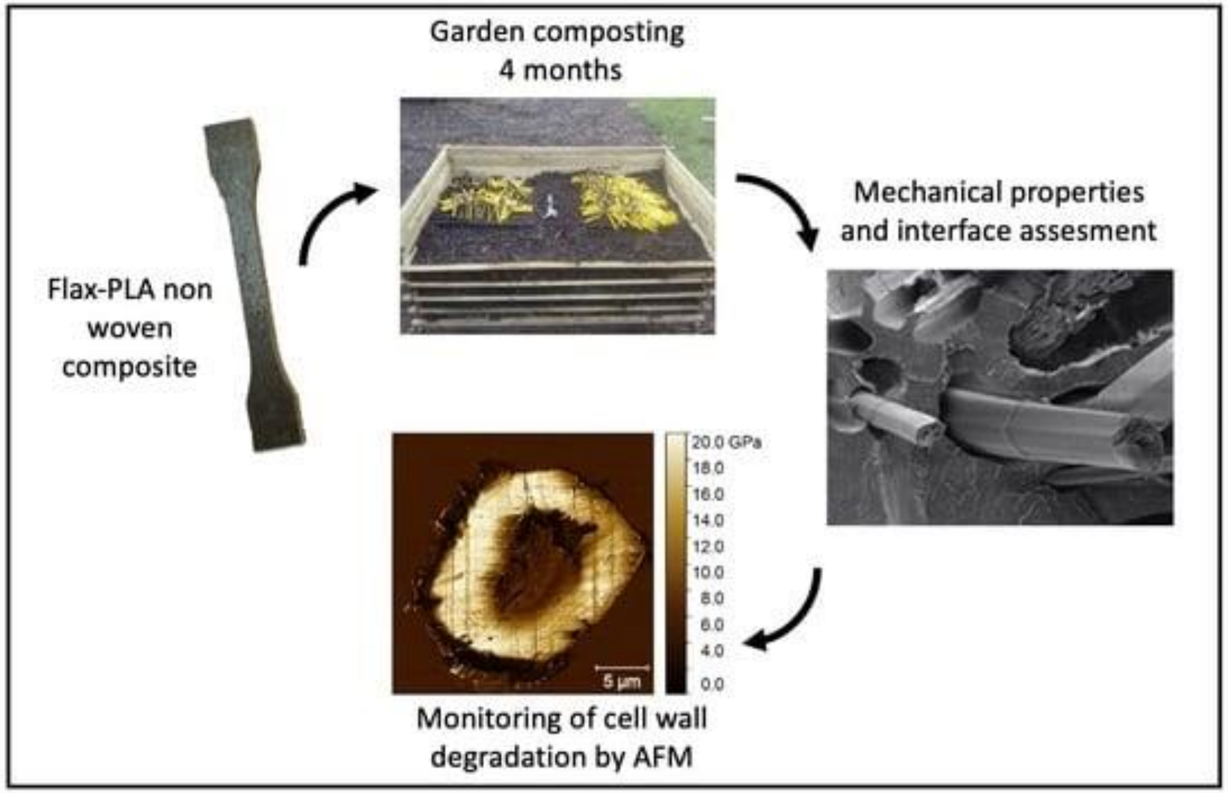
Source: https://www.carbiolice.com/en/carbiosactive/

What are some challenges with using Enzymes?

Cellulose Reinforced PLA for Improved Compostability

- Flax fibers improved strength and biodegradation in soil
- PLA imparts flexibility and transparency



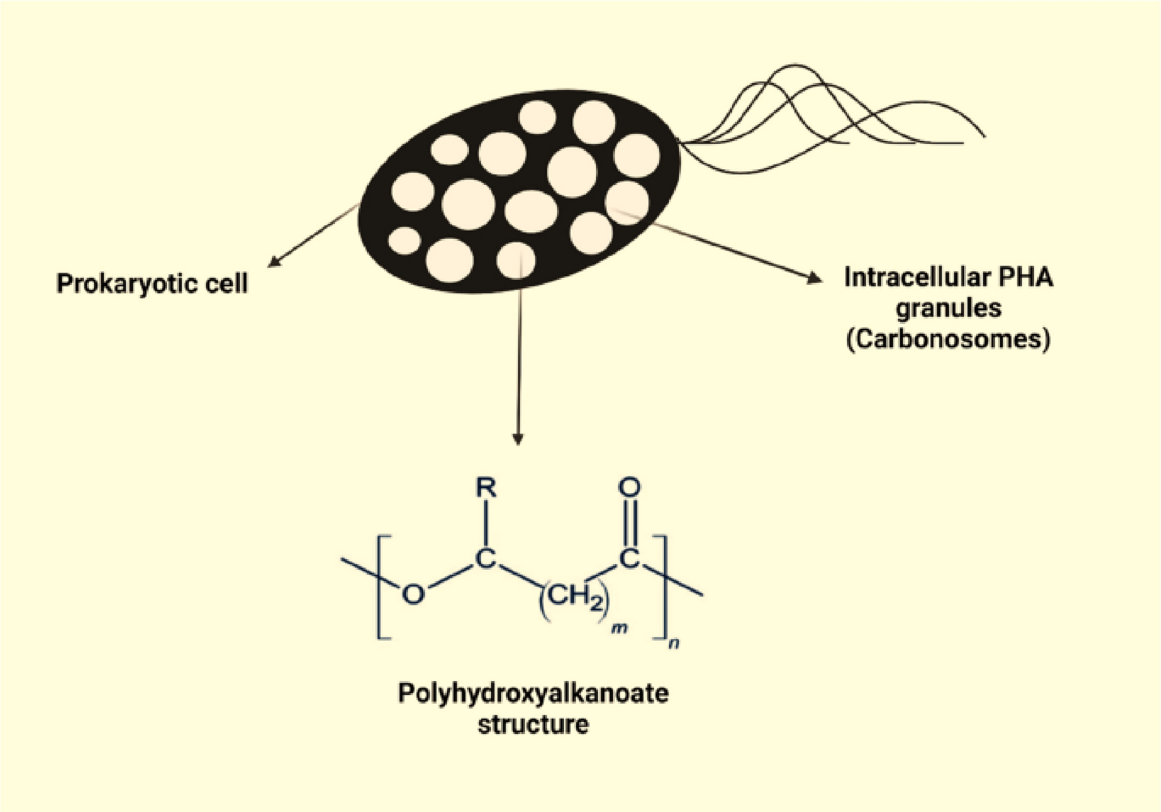


Meleli, A. et al. *Polymers* **2021**

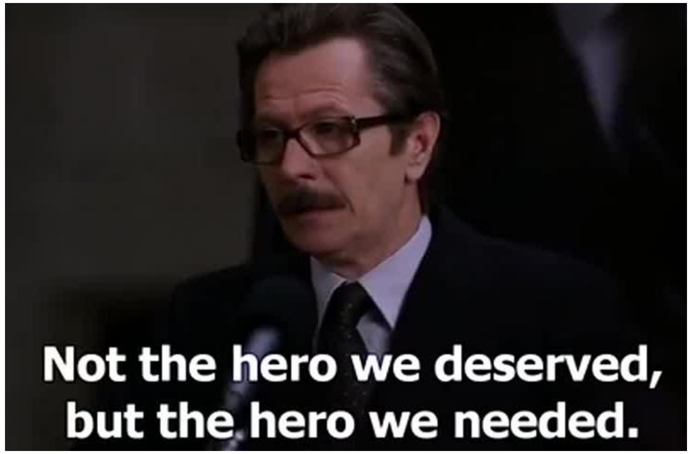
The Pela Story:
Flax-based Elastomers+PLA

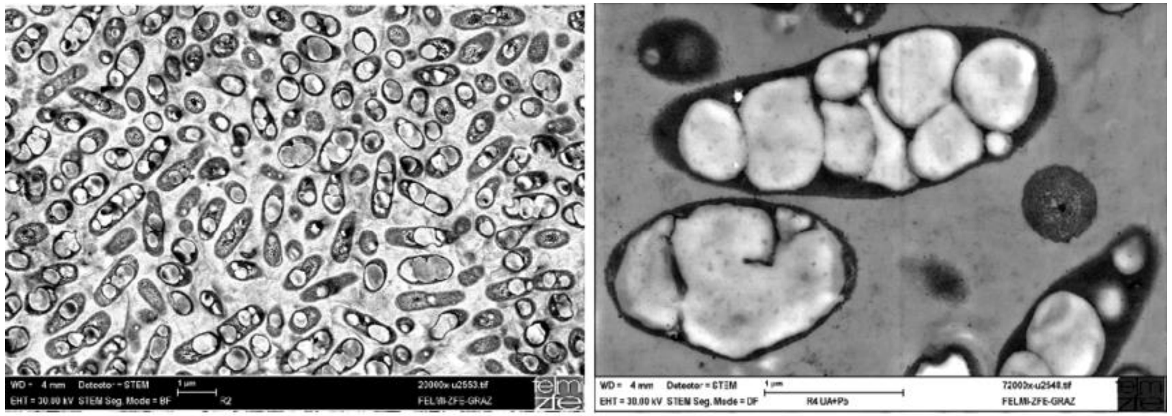
- Biodegradable phone cases and sunglasses
- Made with 45% flax-based elastomer Flaxstic®

PHAs: The Hero We Need?



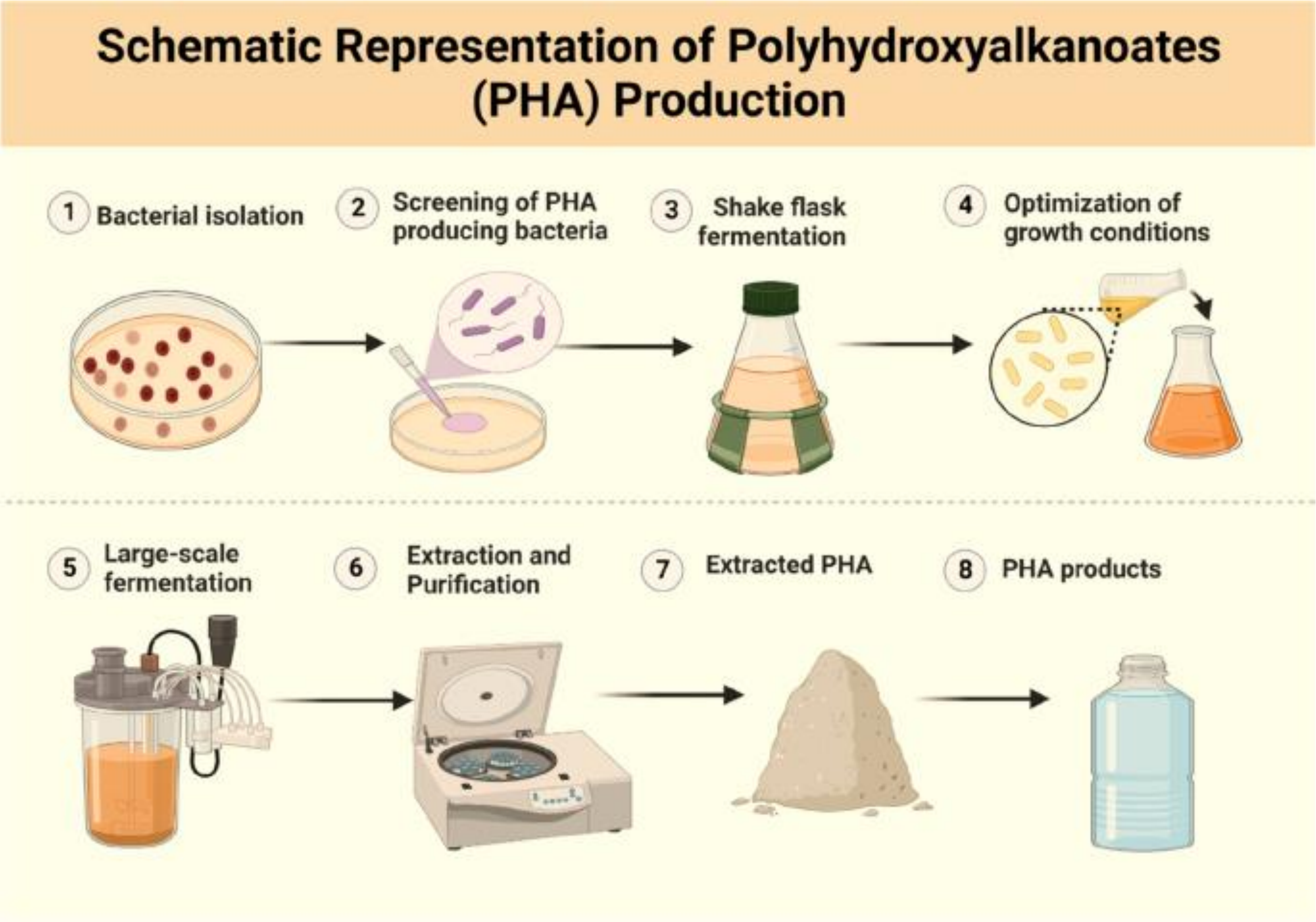
Mahato, R. P. et al. *Archives of Microbiology*, **2023**





- PHAs or Polyhydroxyalkanoates are naturally produced in some bacteria and archaea species
- Naturally-occurring biodegradable polyesters

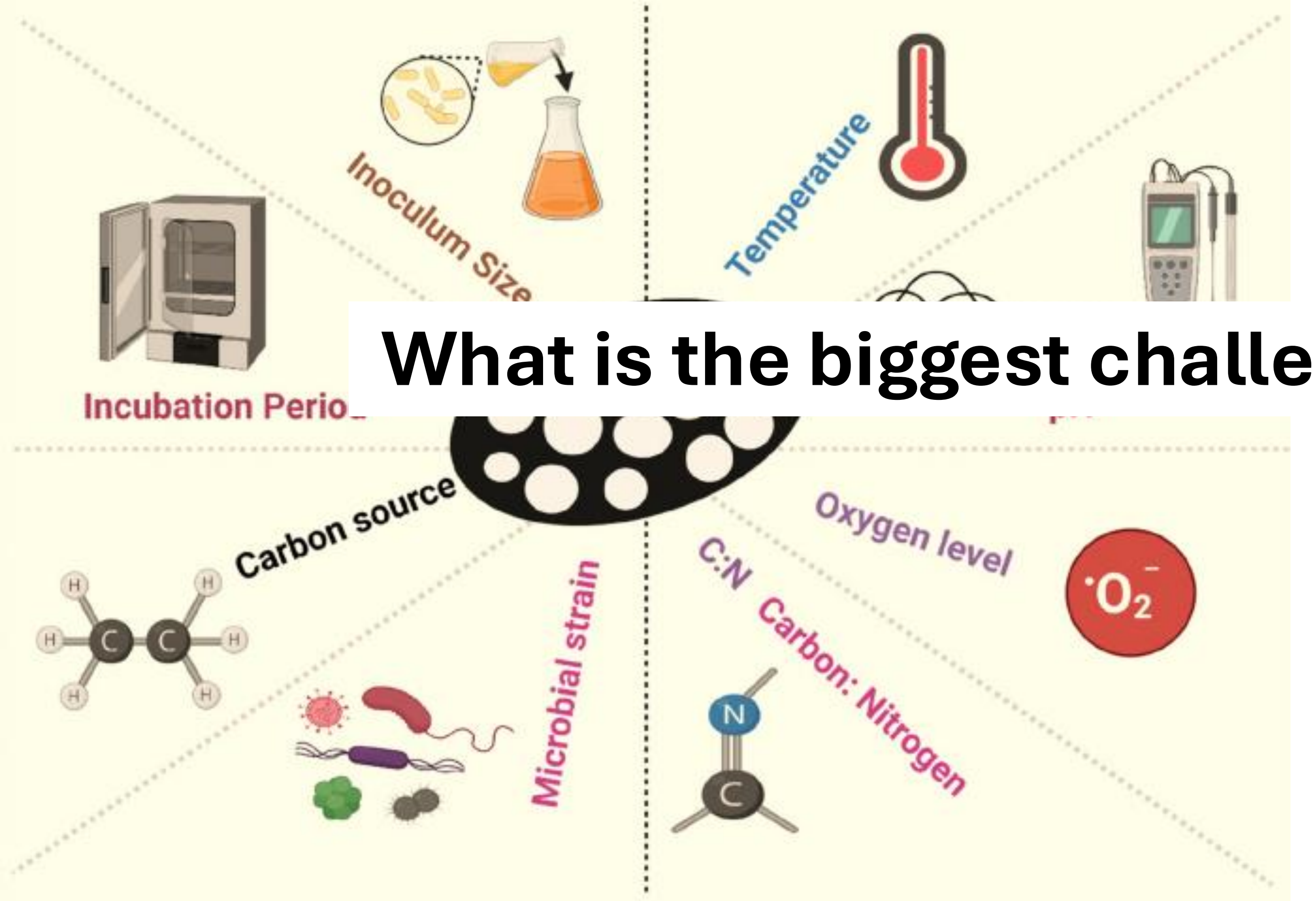
PHAs are Produced via Biofermentation



Mahato, R. P. et al. *Archives of Microbiology*, **2023**

- Microbes are isolated and screened for identifying PHA producing strains
- Microbes may be fermented on small or large scales
- PHA must be extracted and purified prior to use
- PHA is used for application ranging from tissue engineering to consumables

Cost and Efficiency must be Optimzied for Large-Scale Production



Mahato, R. P. et al. *Archives of Microbiology*, **2023**

What is the biggest challenge with PHAs?

- Optimize-
  - Biofermemtation conditions
  - E.g. pH, temperature and time
  - es
  - E.g. microbial strain,multiple strains
  - Carbon source
  - E.g.nutrition source for growing microbes

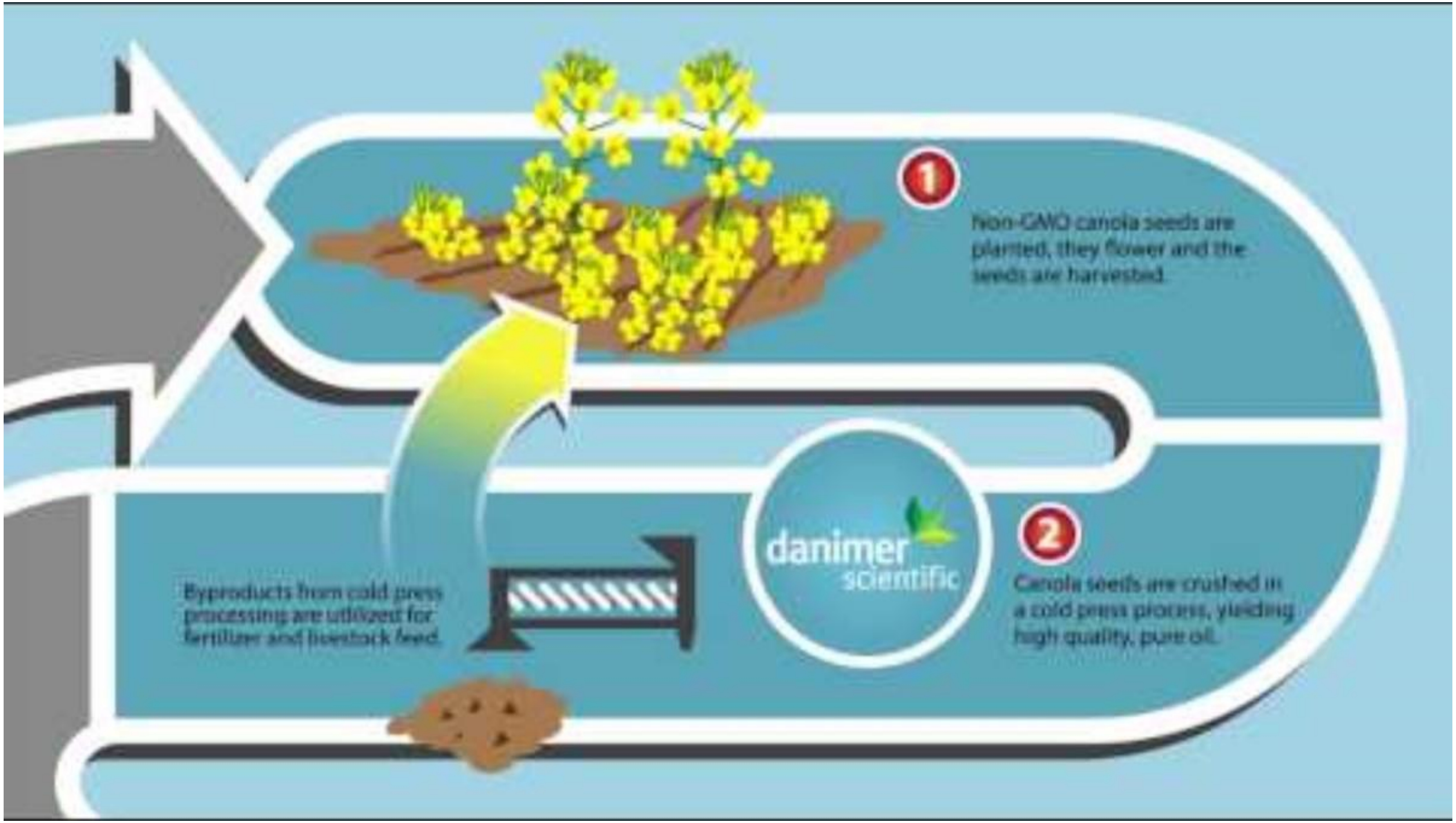
Renewable Carbon Sources Bring Down Costs

Lignocellulose:
- Agriculture waste
- Abundant resource
- Needs Pre-treatment

Plant Oil Waste:
- Byproduct of cold-pressed oils
- High efficiency
- Fatty acid- impacts structure

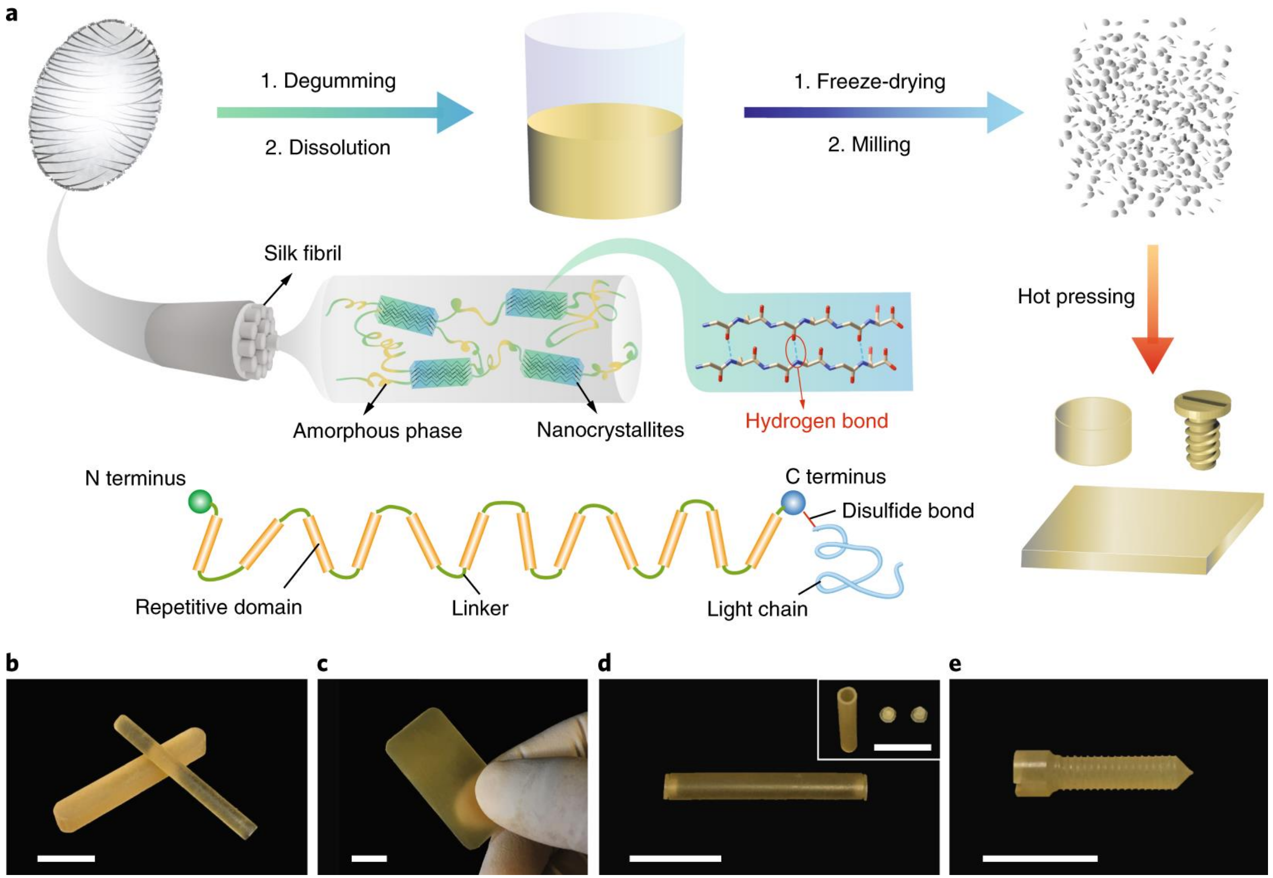
Cheese Whey:
- High in glucose and sugars
- No pre-treatment
- Strain optimization needed

Applications of PHAs



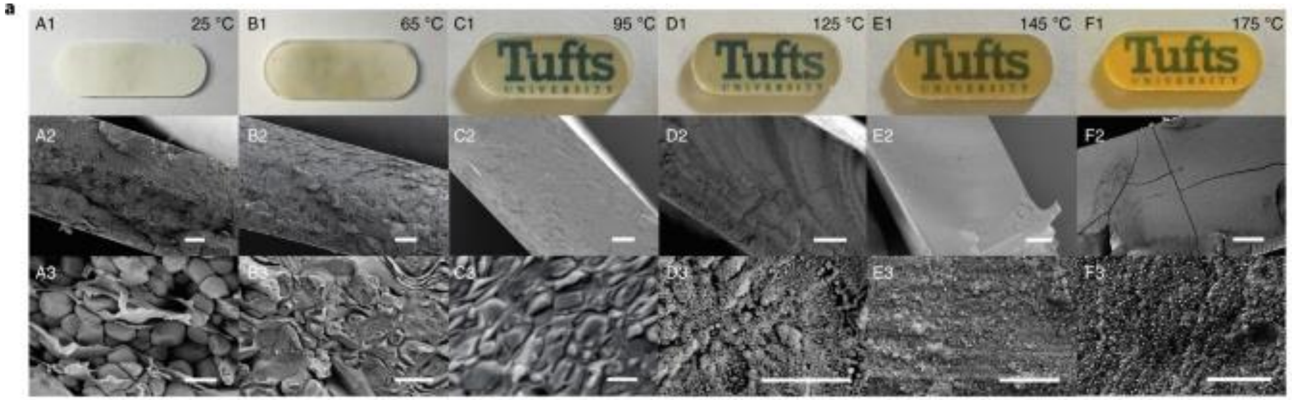
Silk Thermoplastics are Prepared from Silk Fibroin Powder

- Silk fibroin is extracted from silk cocoons and freeze-dried into powder
- Silk powder is hot-pressed in a metallic mold to prepare plastics
- Plastics are rigid and strong. May also be machined

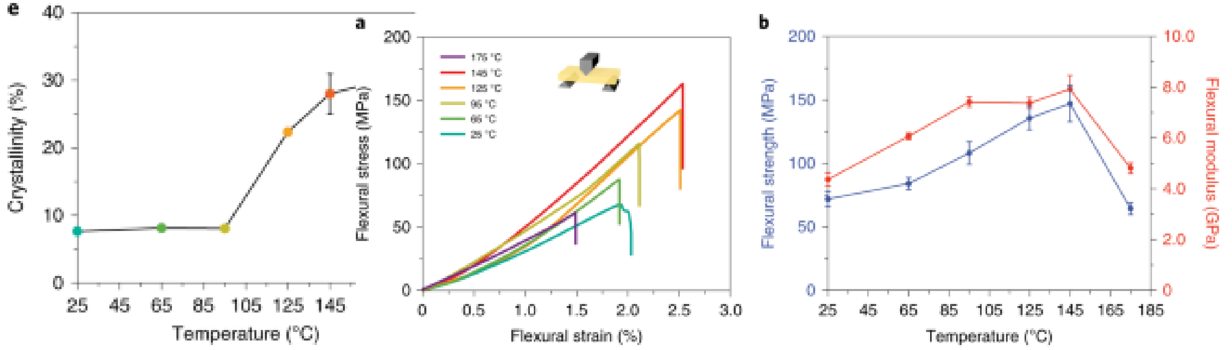


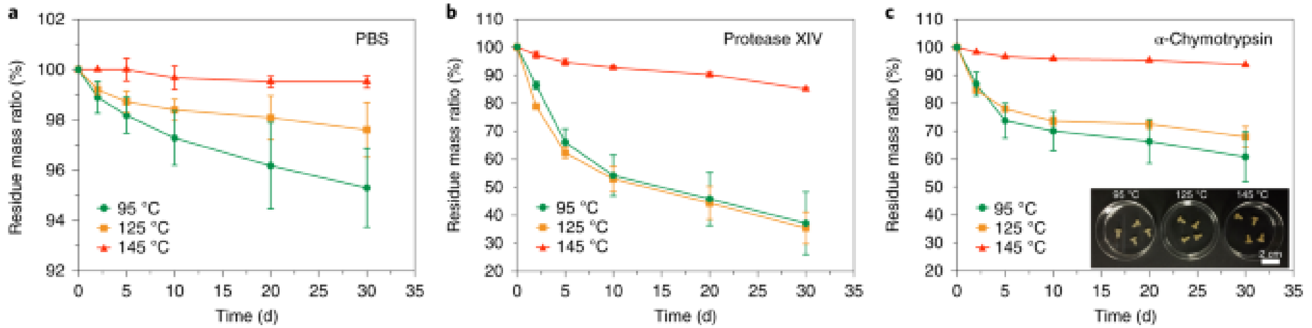
Guo, C. et al. *Nature Materials* **2020**

Varying Temperature and Pressure Modulates Plastic Properties



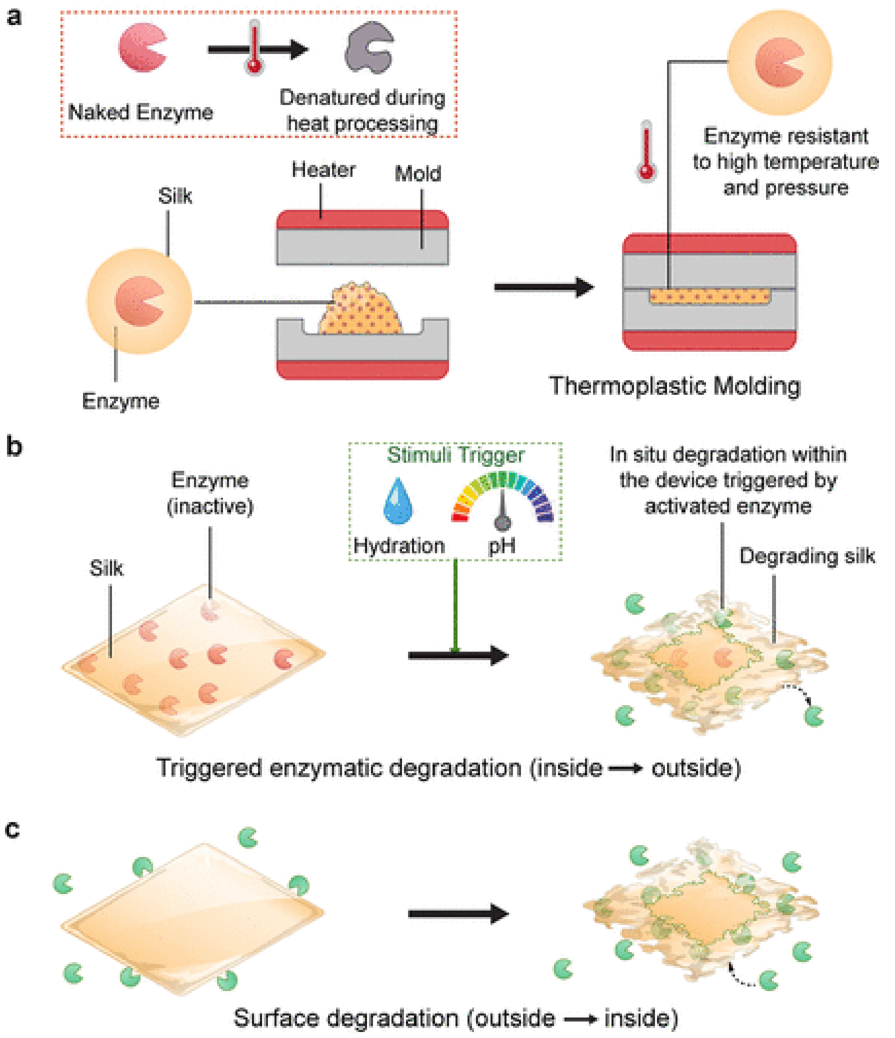
- Increased Optical transperancy and crystallinity at higher temperatures
- Changes in mechanical properties based on treatment temperatures
- Changes in enzymatic degradation rate due to treatment temperatures

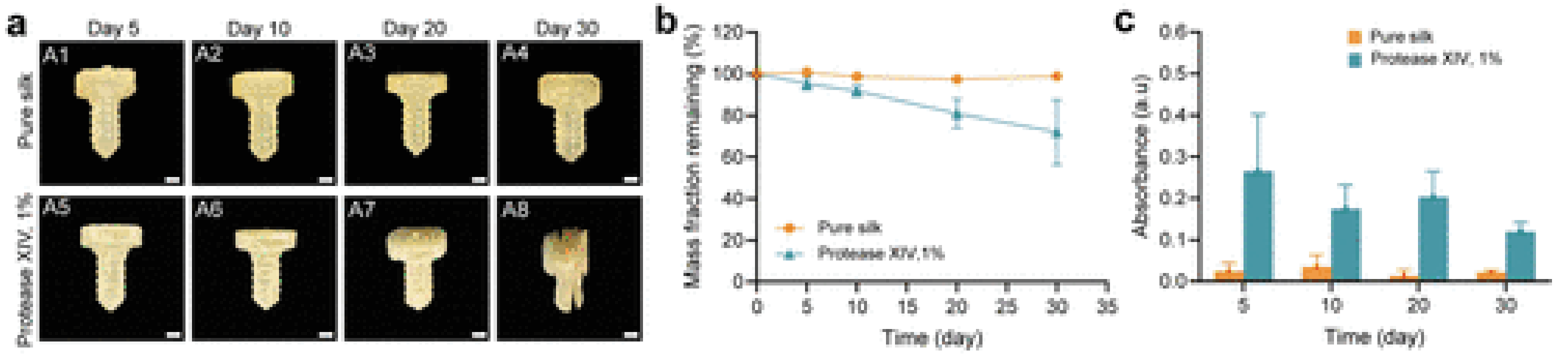




Guo, C. et al. *Nature Materials* **2020**

Silk Plastics Loaded with Enzymes to Facilitate Degradation



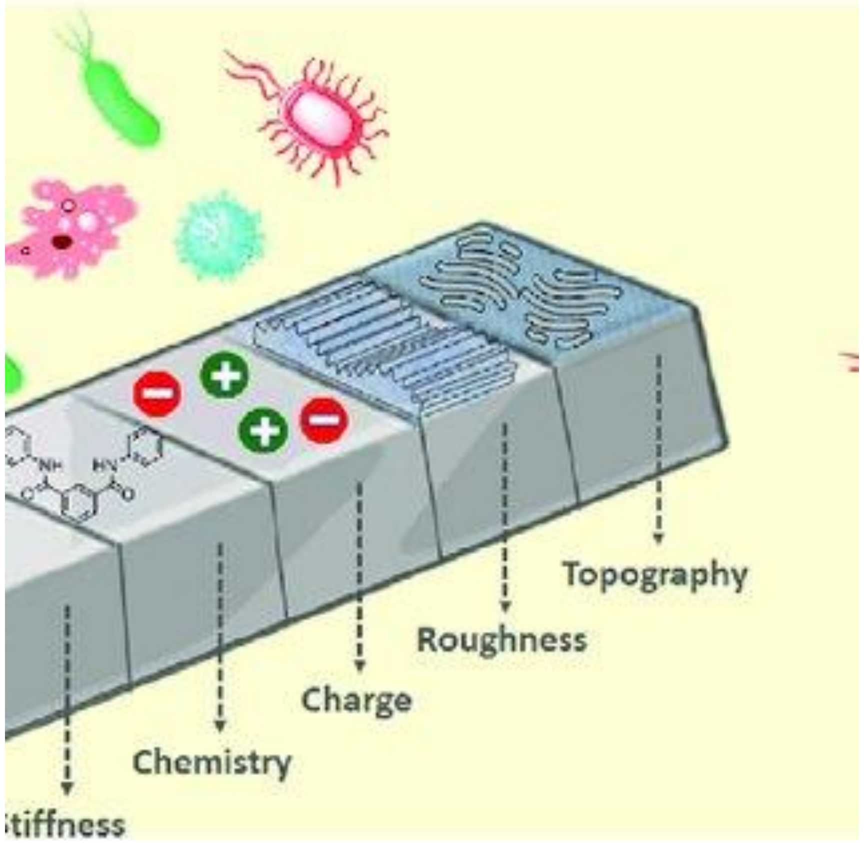


- Silk acts as protectant during thermopressing
- Enzyme activity is preserved
- Facilitates inside to outside degradation

Wu, J. et al. *ACS Biomaterials Science and Engineering* **2024**

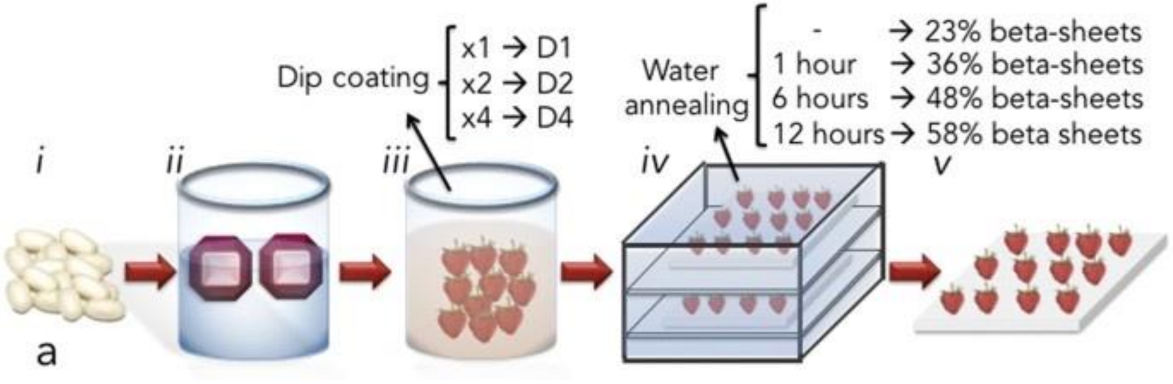
Biopolymer Coatings Impart Surface Functionality to Materials

- Surface properties such as charge, roughness and hydrophilicity may be modified using biopolymer coatings
- Biodegradable and green surface modification techniques for all materials and devices

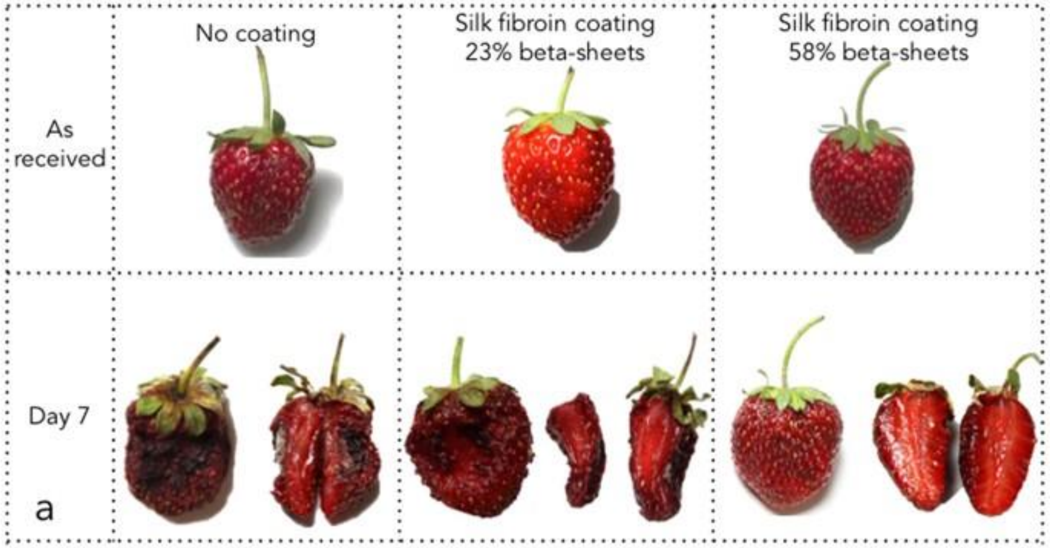


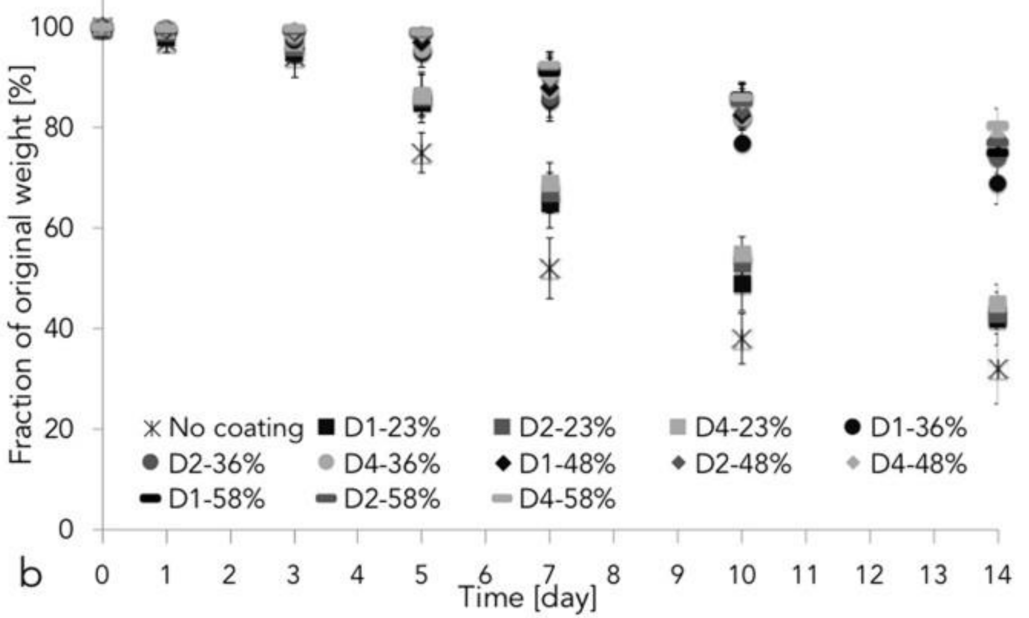
Nouri, A. et al. *Smart Materials in Manufacturing*, **2023**

Silk-based Edible Coating for Improved Food Storage



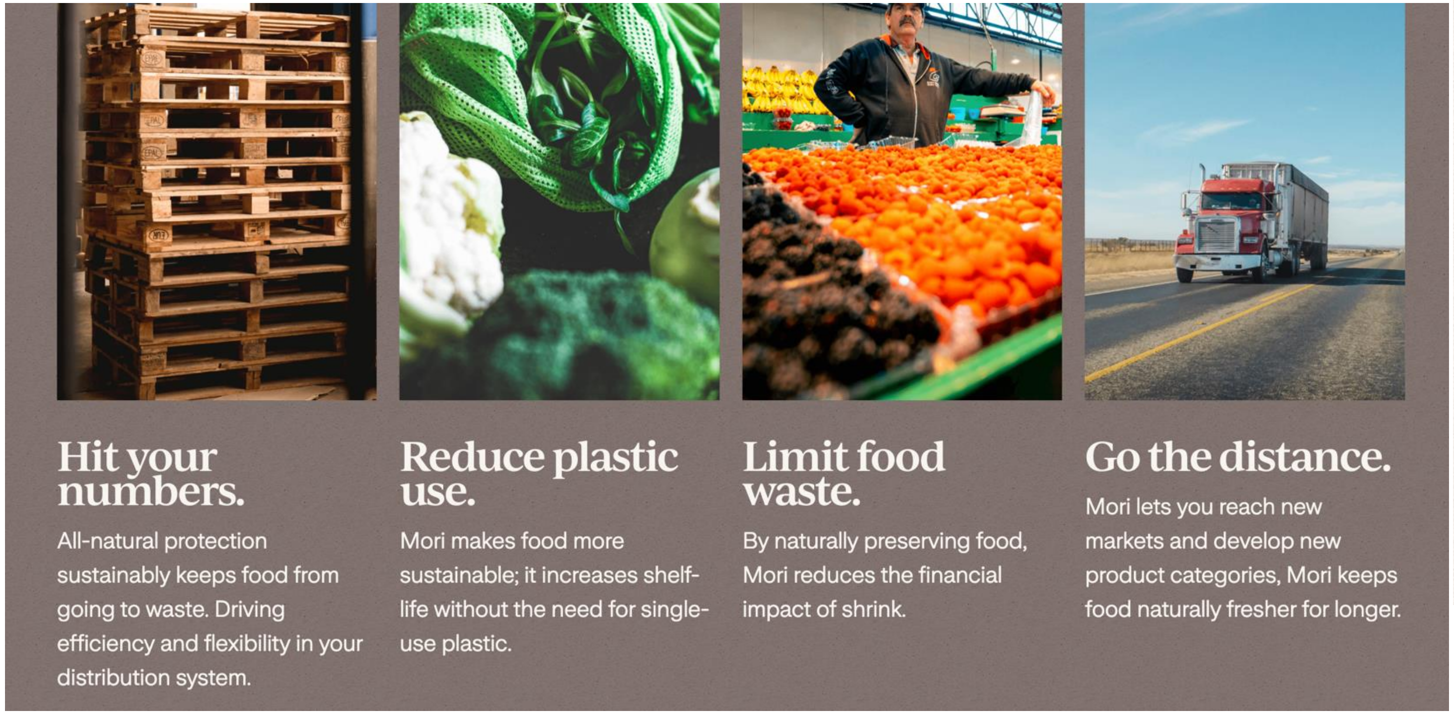
Marelli, B. et al. *Scientific Reports*, **2016**

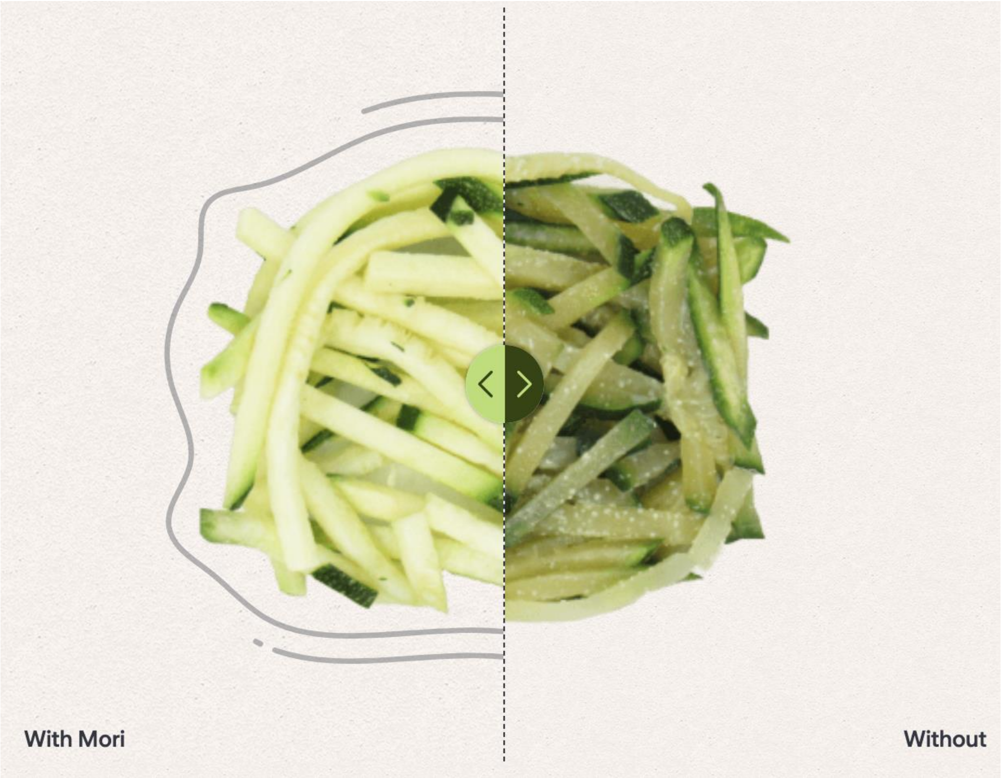




- Silk fibroin is dip-coated onto food and water annealed to induce beta-sheeting
- Coating improved moisture retention, prevent weight loss and decay of food
- Edible, food-grade coating

Mori: Edible Silk Coating for Food Storage and Preservation

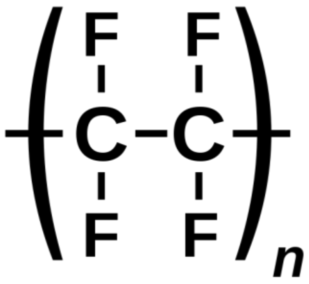


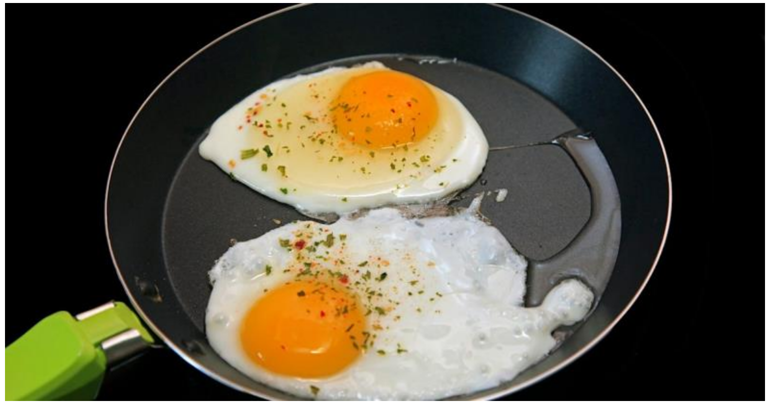


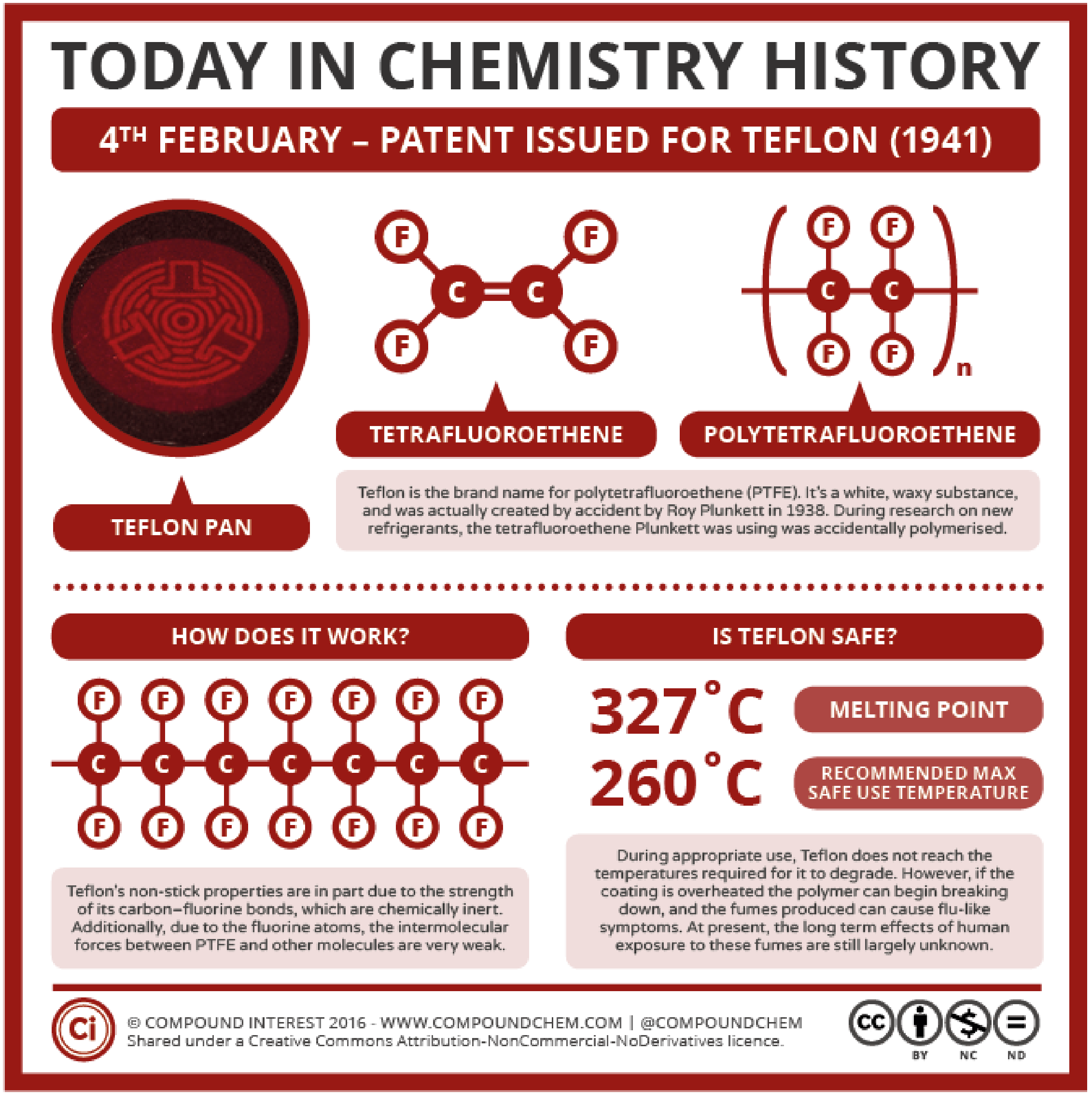
- Silk coating prevents –
  - Moisture loss
  - Air contact
  - Bacteria/ mold growth

mori

Hydrophobic Biopolymers: Teflon Alternatives

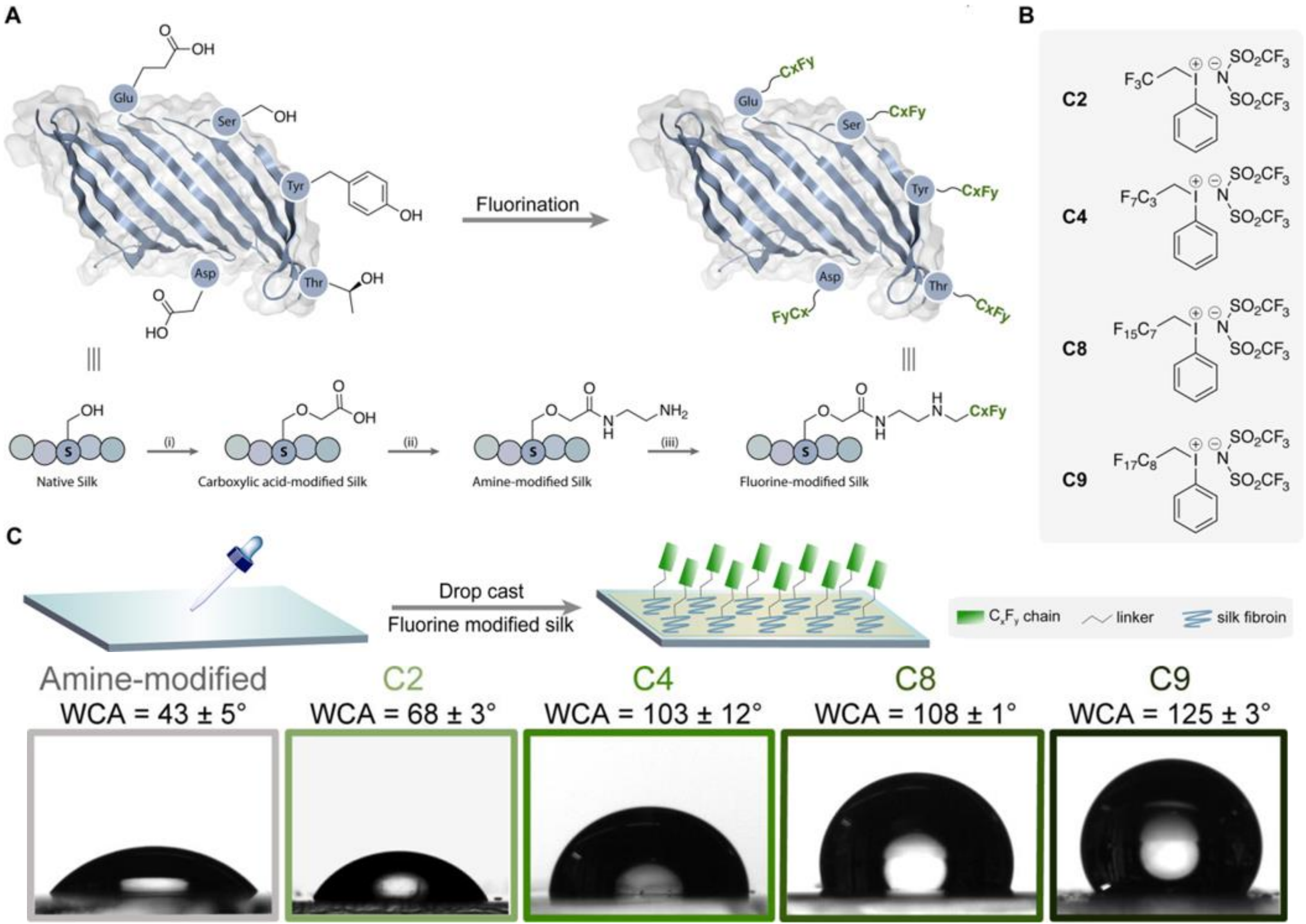






- Hydrophobic coatings like Teflon are prepared from fossil fuels
- PFAS exposure and release is an environmental concern

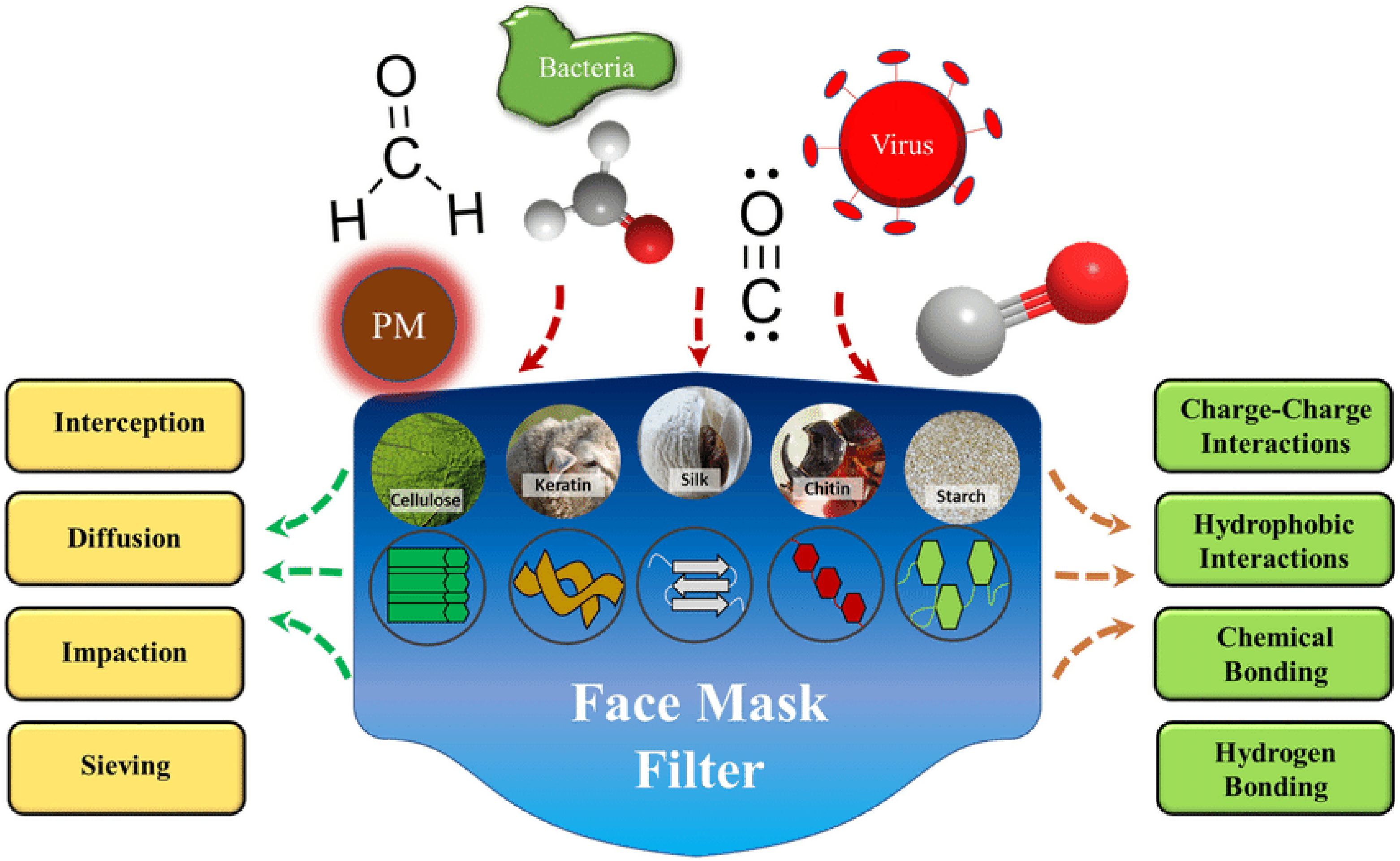
Fluorinated Silk as Biodegradable Alternative for Teflon



- Biodegradable Alternative
- High water contact angles
- Still using perfluorocarbons

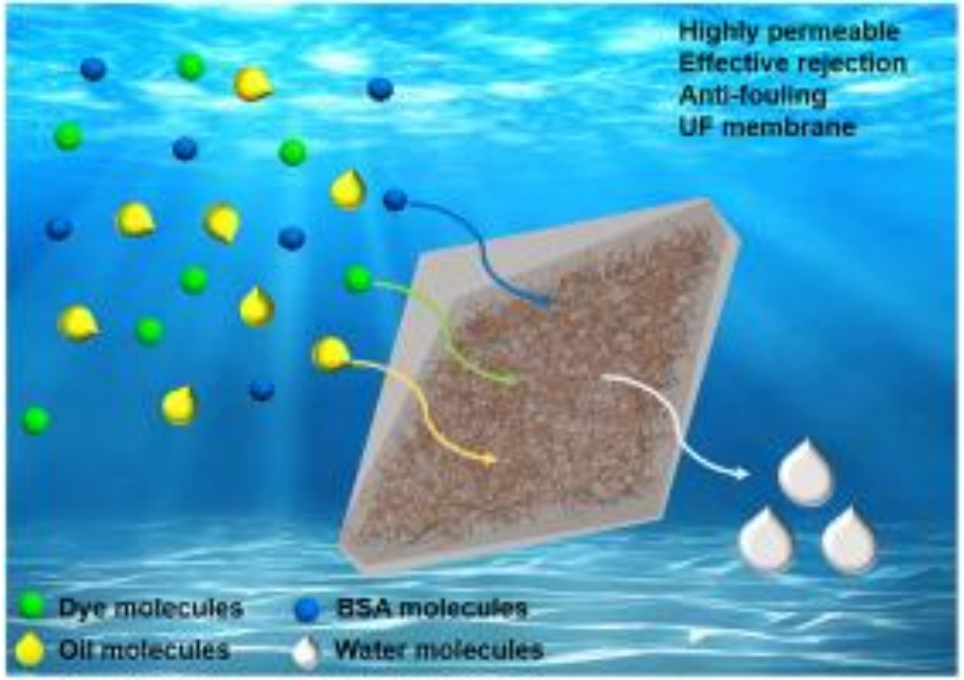
Fountain, J.N. et al. *Chem BioChem*, **2022**

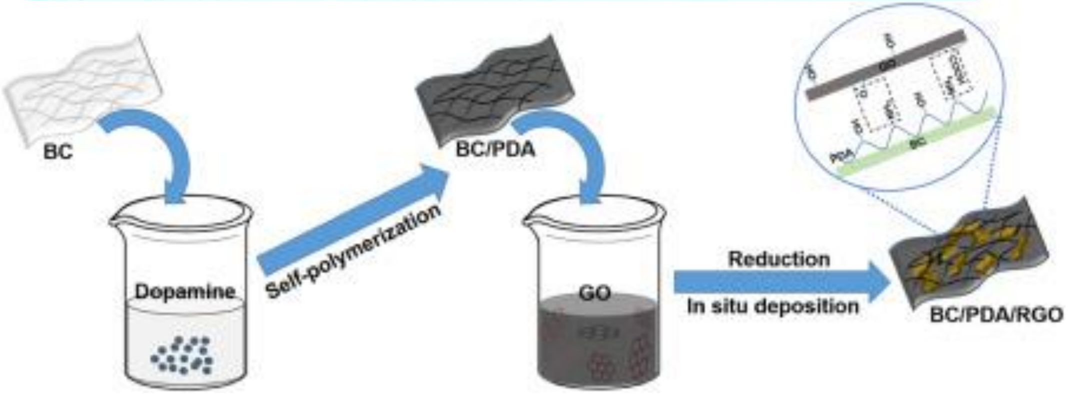
Biopolymers as Filtration Membranes

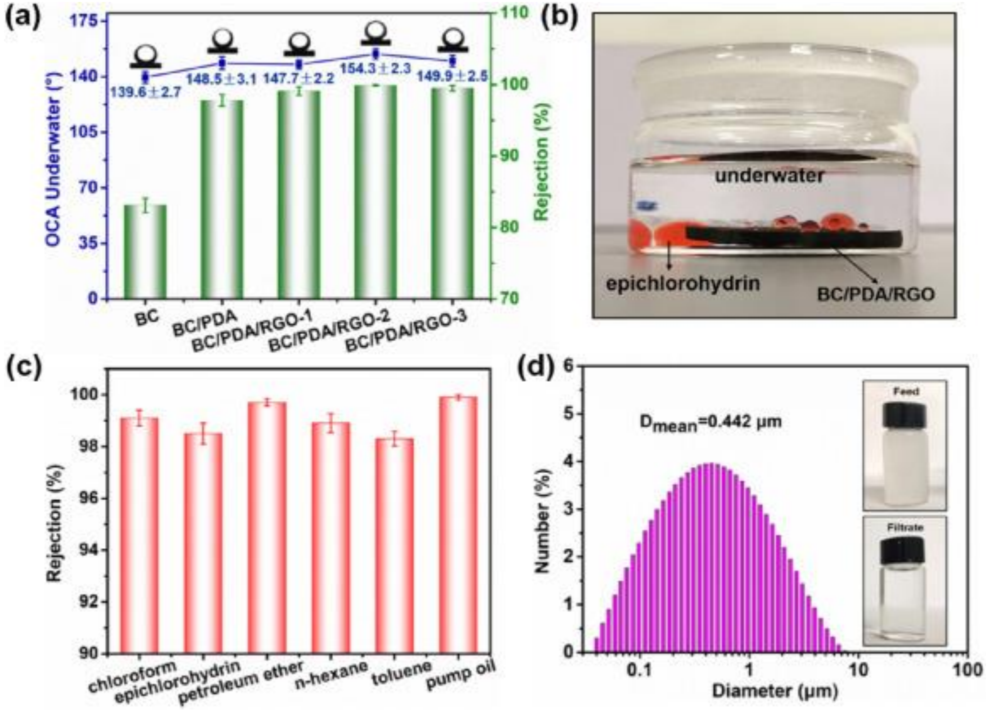


- Modifiable with green chemistry and fabrication techniques
- Biodegradable – ideal for single use
- Non-toxic and safe

Bacterial Cellulose Filtration Systems for Wastewater



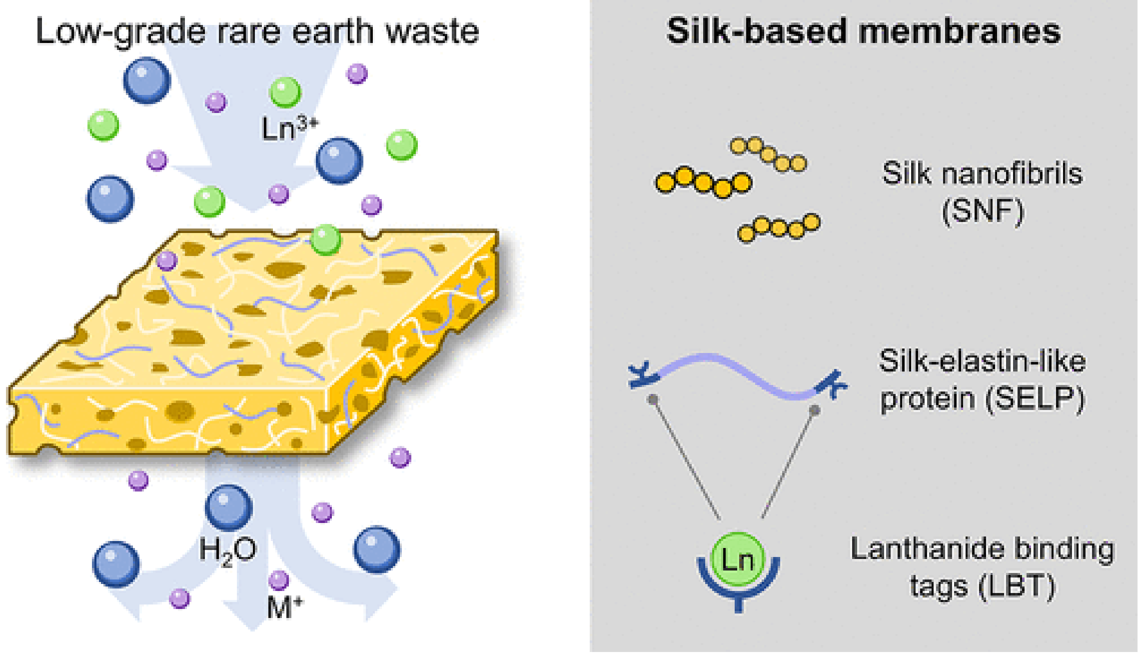


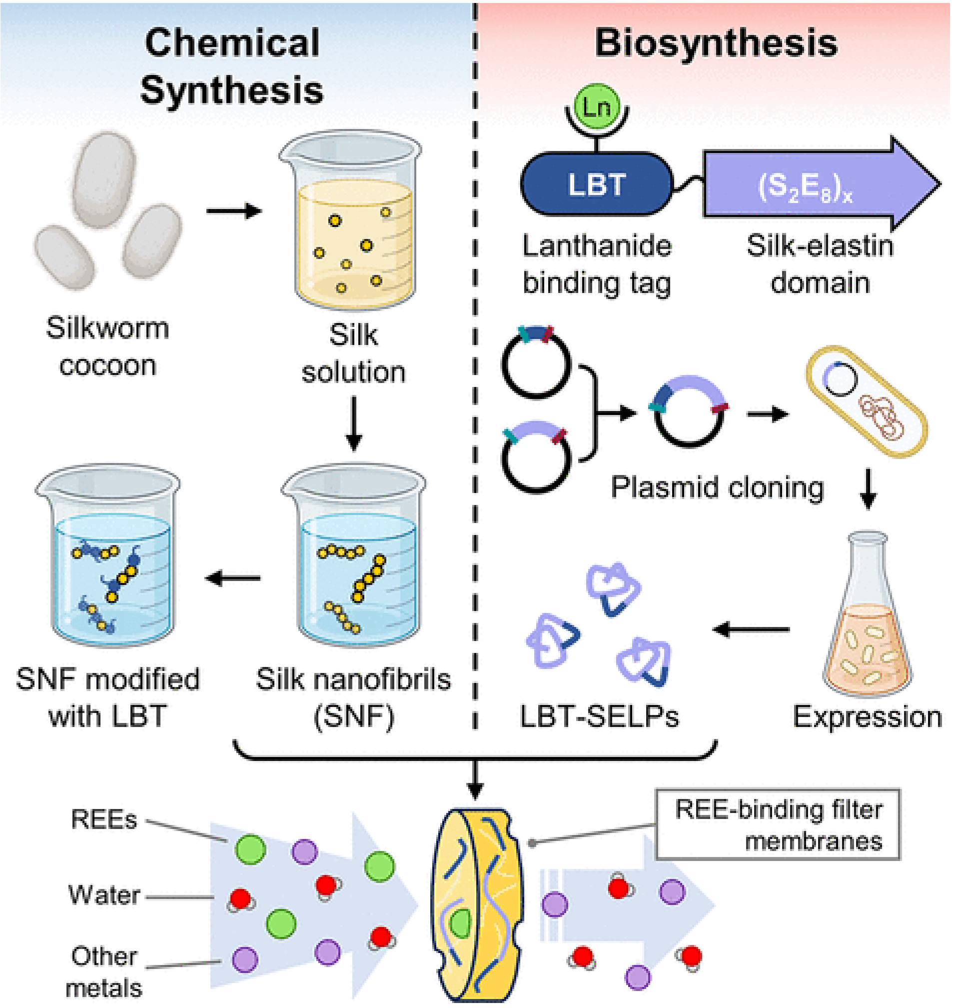


Hu, Y. et al. *Journal of Membrane Science*, **2021**

- Polydopamine coated BC membranes show good affinity for most oils and dyes
- Wastewater treatment strategy

Silk Membranes utilized for Recovering REEs

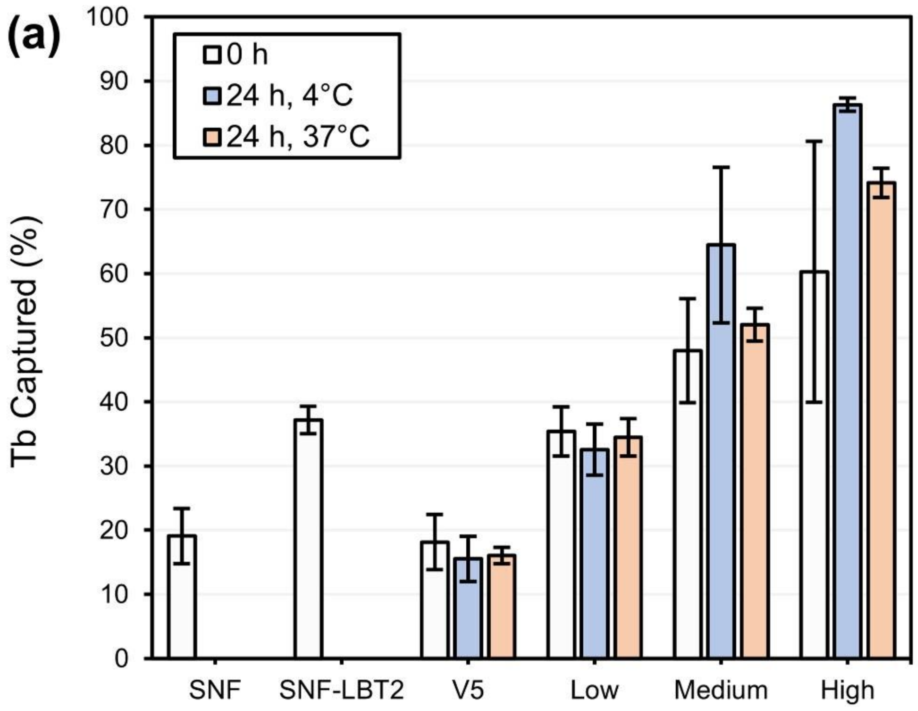


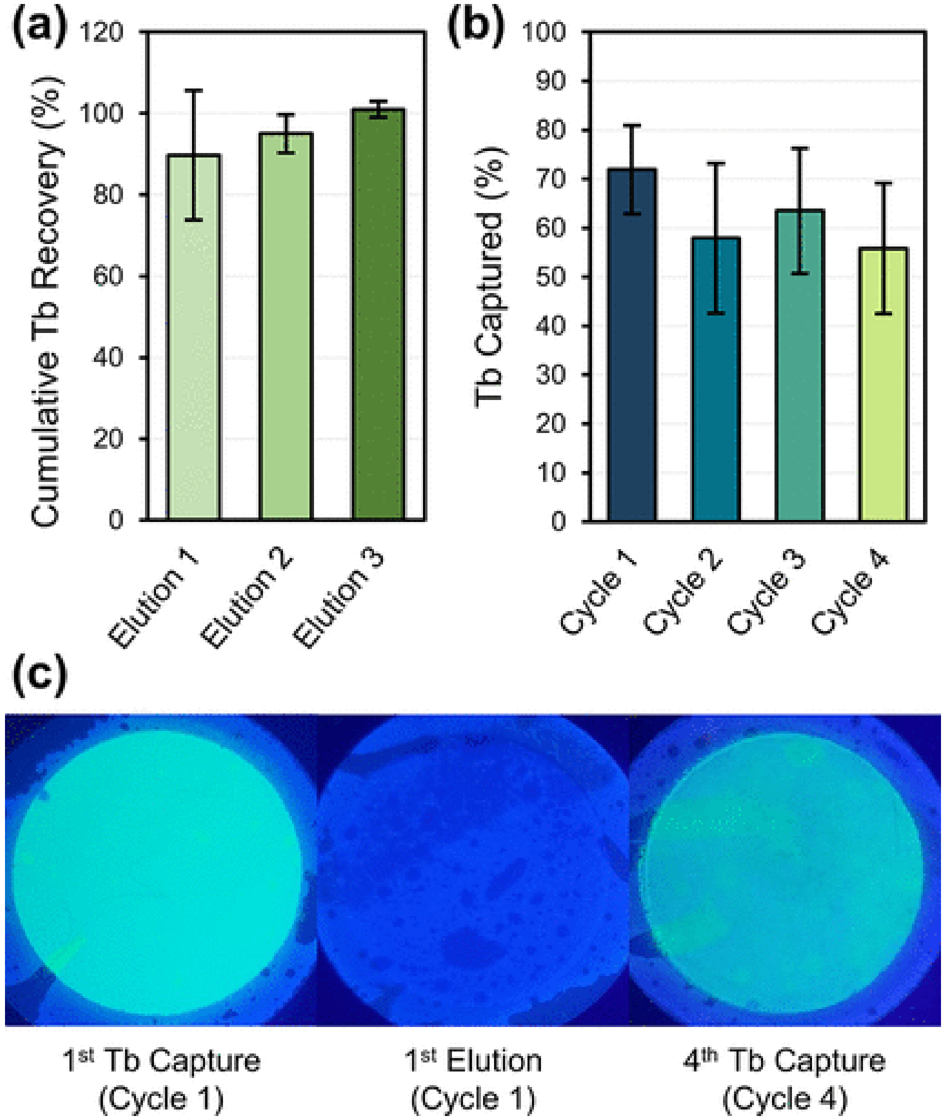


- Silk membranes modified to include a Lanthanide binding moiety
- Can purify and recover rare-earth elements from waste streams
- Reduce mining of rare-earth elements

Scheel, R. A. et al. *ACS ES&T Engg*, **2024**

Silk Membranes utilized for Recovering REEs

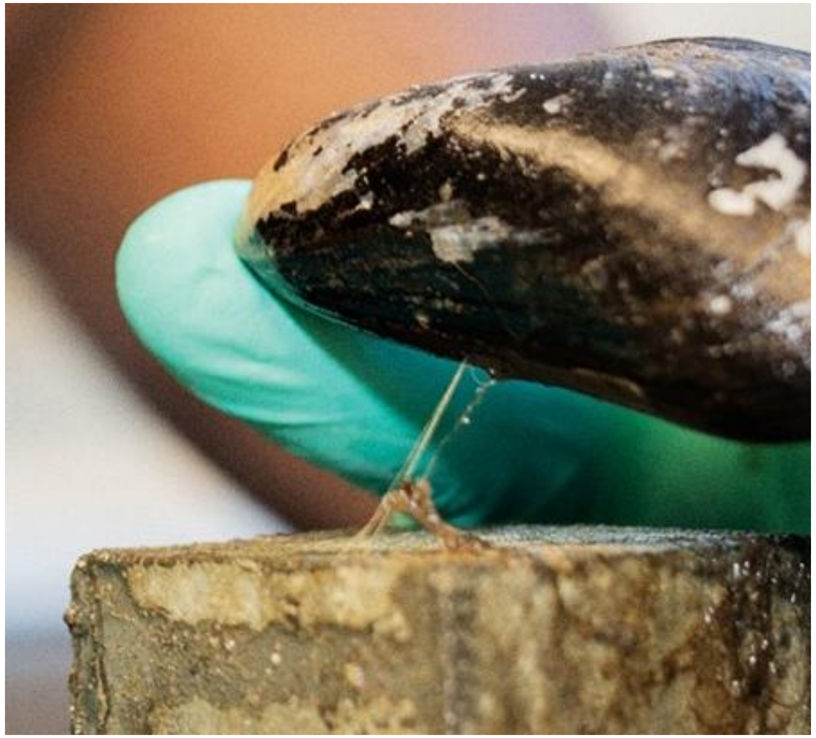


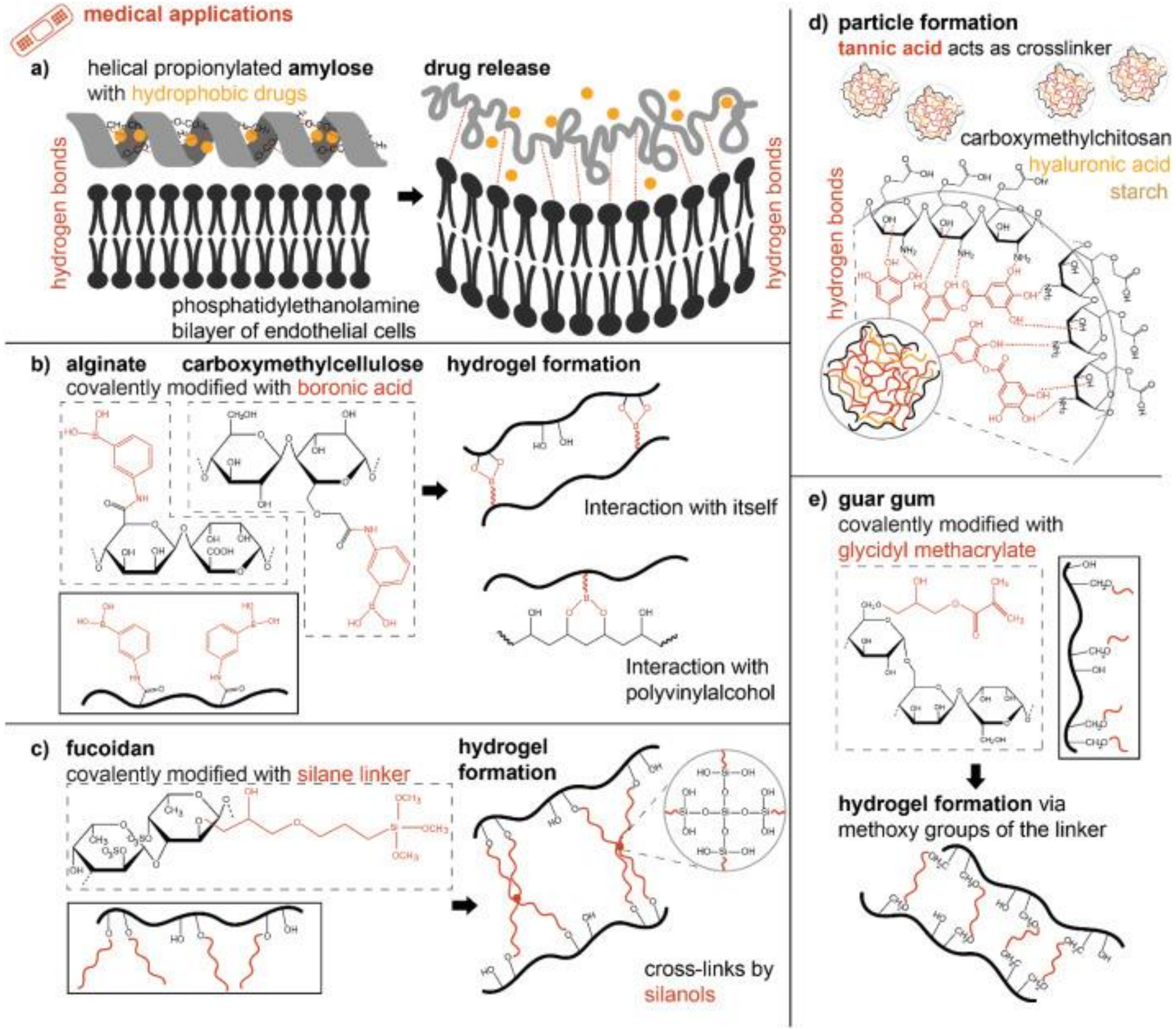


- Upto 80% Terbium captured from solution
- Terbium recovered by eluting membrane with acidic solution
- Membrane is reusable

Scheel, R. A. et al. *ACS ES&T Engg*, **2024**

Biopolymer-based Adhesives





- Adhesives made from biopolymers inspired by adhesive materials in nature

Biopolymer-based Elastomer Alternative to Silicones

BOLT THREADS

B-SILK™ VALUE PROPOSITION

B-silk™ is result of **13+ years of deep R&D**. Now, this patented and proprietary polypeptide is ready to effectively meet the market demand **to replace silicone elastomers across Beauty & Personal Care**—

BIOBASED & BIODEGRADABLE

Unlike silicone elastomers, b-silk™ is biodegradable

B-silk™ is USDA Certified Biobased product

Vegan Verified by Eurofins Chem-MAP

Microbiome friendly

FORMULATOR FRIENDLY

B-silk™ is highly versatile — it is stable, robust, and does not negatively react with other ingredients found in skincare, suncare, color cosmetics, or haircare.

CLINICALLY PROVEN CONSUMER BENEFITS

B-silk™ has been on the shelf in hair care products since 2020 and boasts 20+ established benefits, including giving the appearance of firmer and more elastic skin, making the cosmetic signs of aging less noticeable, increased pollution cleansing, hair curl retention, and more.

B-silk™ Value Proposition & Market Differentiators — 35

- Silicones provide the slip and smoothness in many cosmetic and medical products
- Fossil fuel generated, many health and concerns
- Recombinant spider silk-based alternative produced from bioengineered yeast

Final Thoughts!

- Biopolymer replacements for traditional synthetic polymers have several applications
- Cost of manufacturing, cost of goods is still a concern
- **Is scale-up feasible?**
- **Can existing manufacturing techniques be translated for biopolymers?**