Opportunities for Innovation in Sustainable Materials

Presented by Dr. Lauren Blake

Sustainable Materials Course

Lecture 5-6

Introduction
- Overview
- Historical Perspective

Challenges
- Human Health
- Environment
- Opportunities

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

Applications
- Food and Ag
- Electronics and Optics
- Healthcare

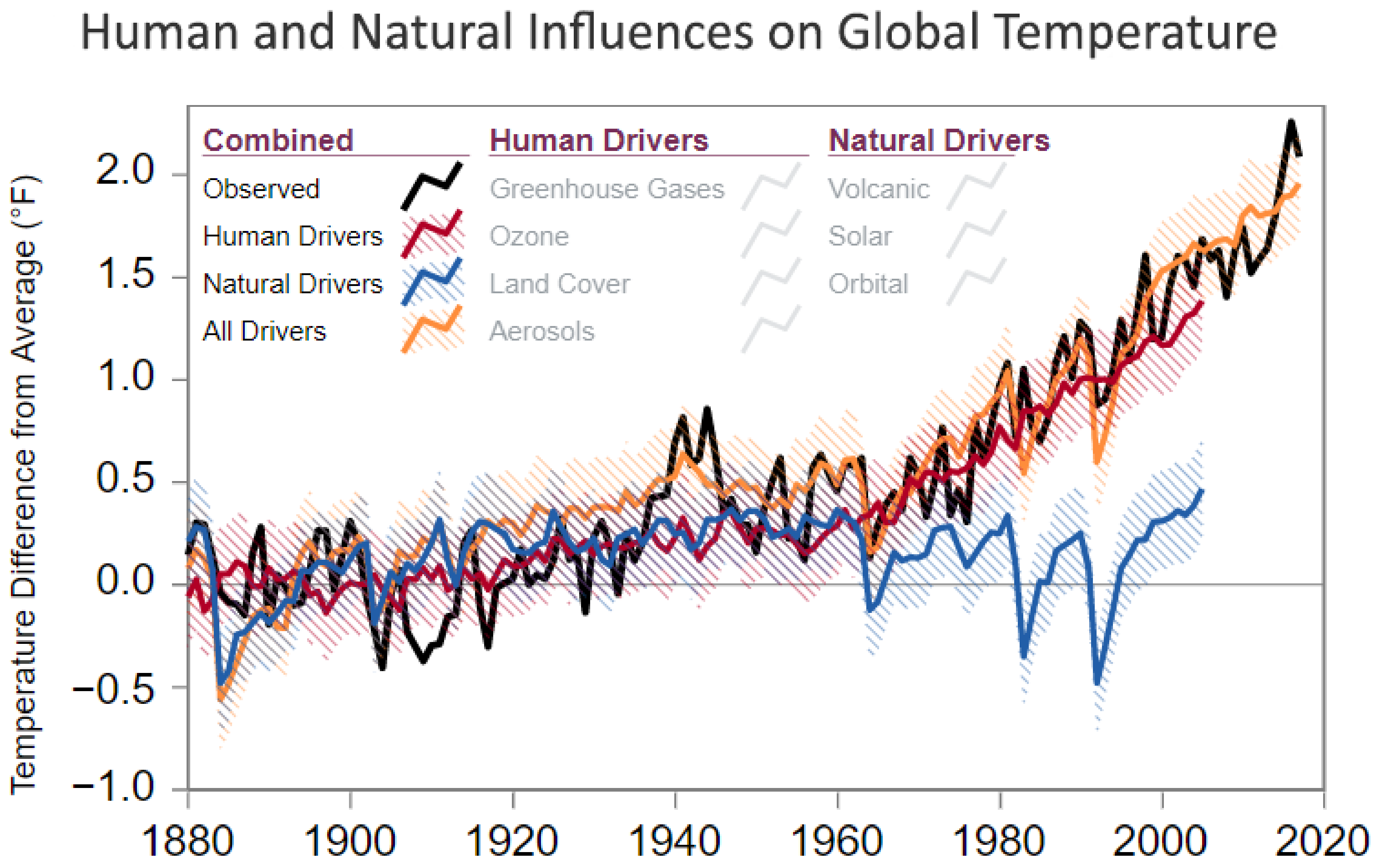
Future
- What do we need?
- How do we get there?

Learning Outcomes

1. Name three unique opportunities within sustainable material design
    1. Carbon capture
    2. Remediation
    3. Biomanufacturing
2. Understand the caveats and obstacles within each new opportunity area
3. Career opportunities within sustainable materials

Carbon Capture

Climate change is a result of natural and human drivers

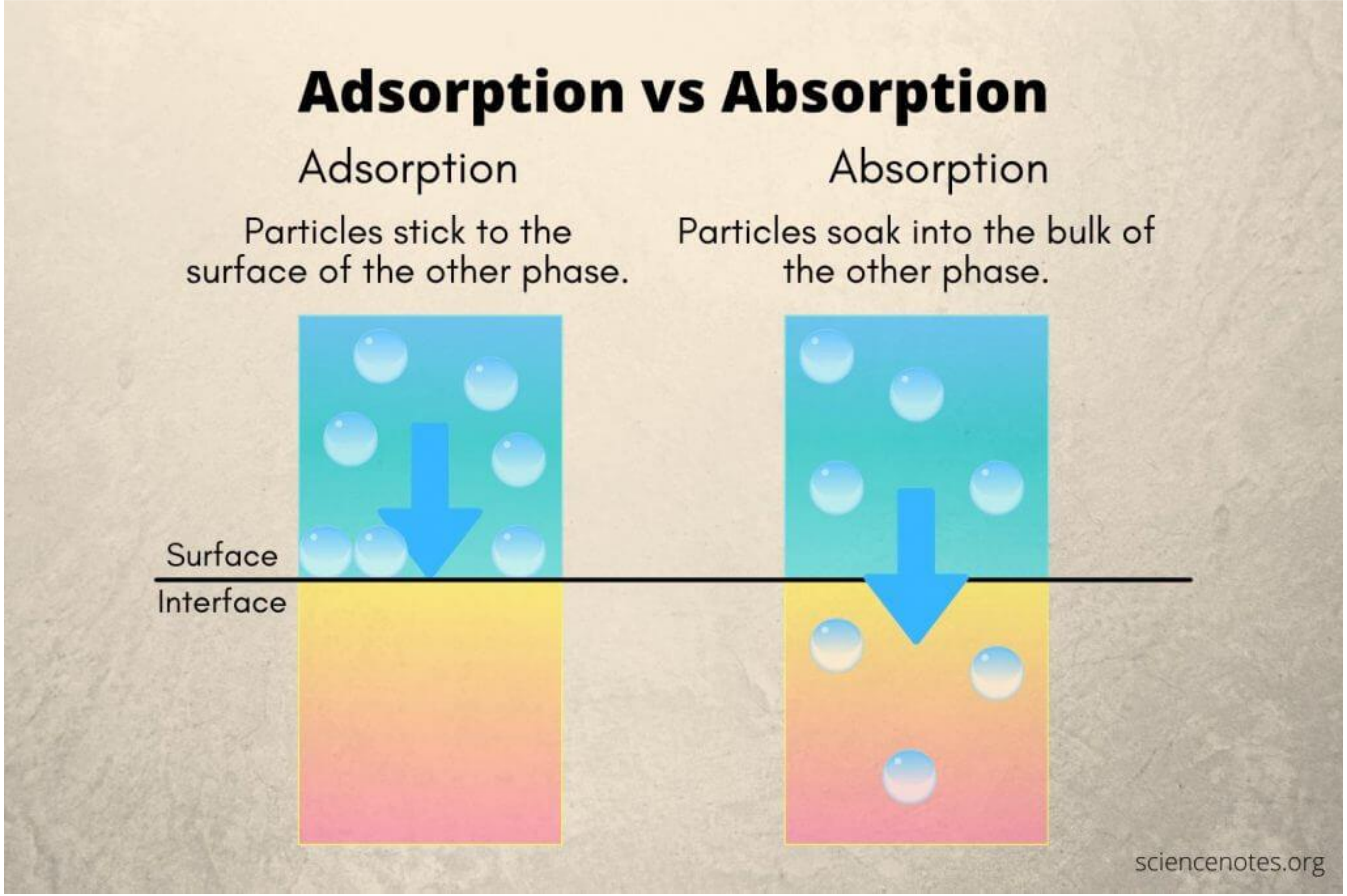


Human interventions:

- Greenhouse gases: carbon, methane, nitrous oxide, are being released at an **all-time high**
- Land cover and foliage at an **all-time low**

Source: U.S. Global Change Research Program, Fourth National Climate Assessment, [Chapter 2: Our Changing Climate], 2017.

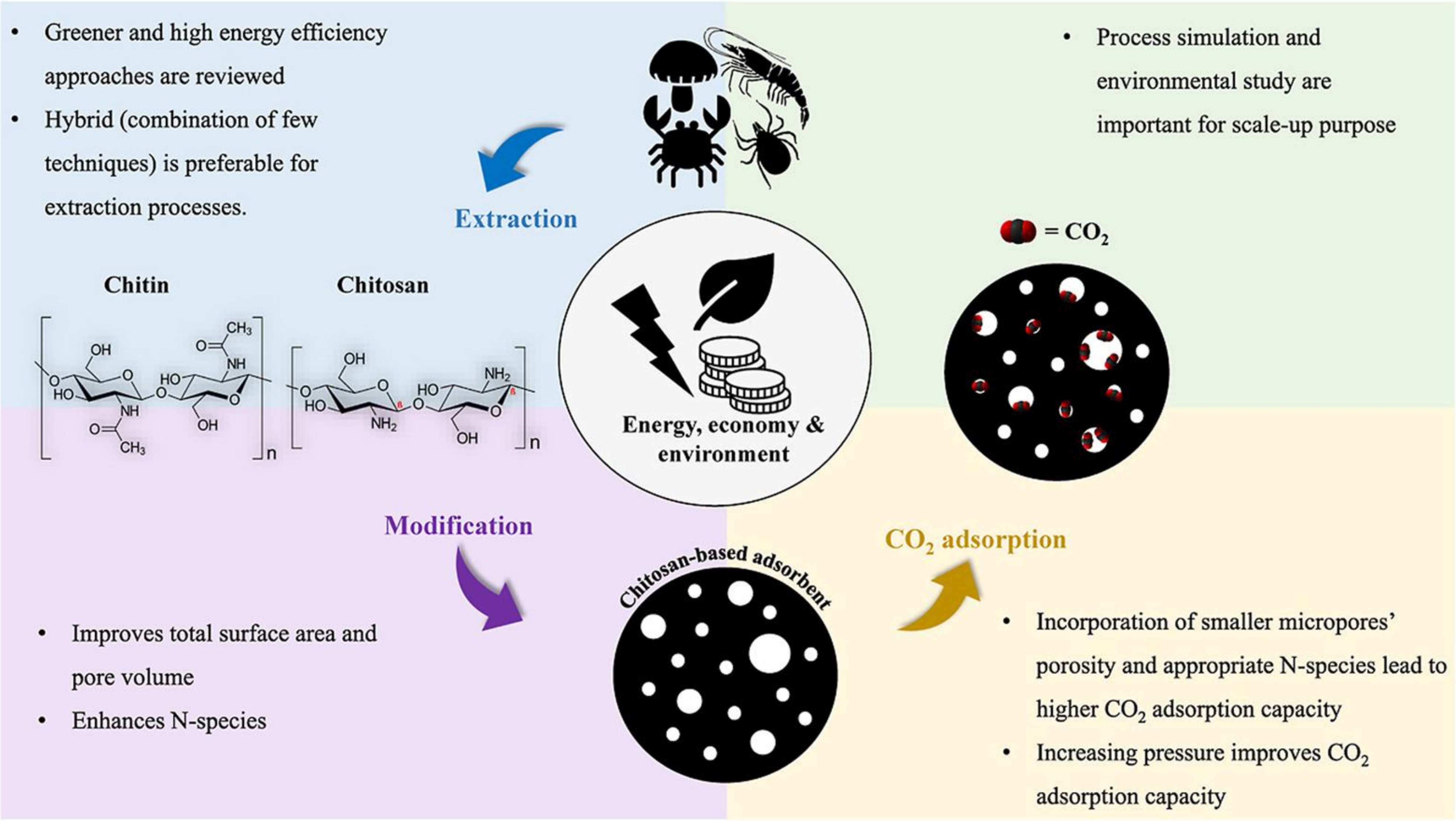
Carbon capture can occur via absorption or adsorption



Carbon capture can occur via adsorption onto chitosan

Adsorption:

adhesion of atoms, ions or molecules from a gas, liquid or dissolved solid to a surface

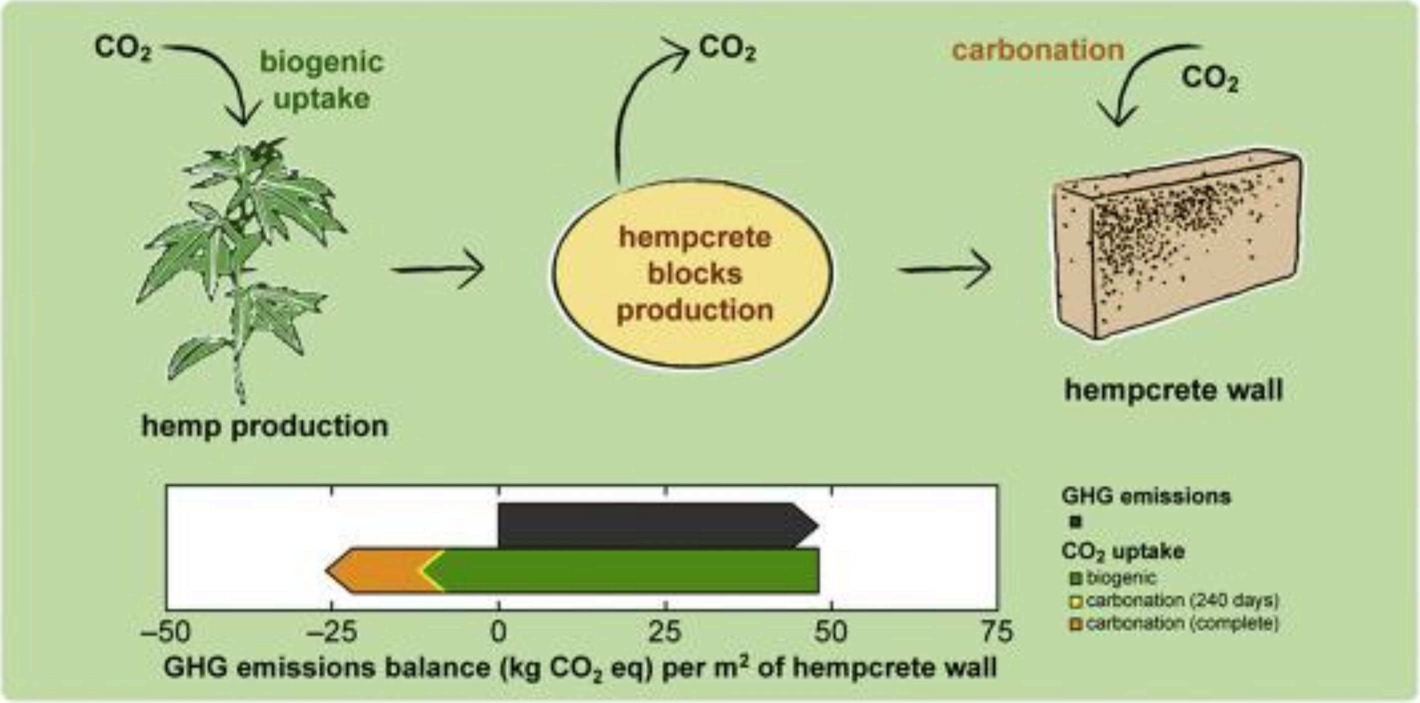


Foong et al. Sustainable CO_2 capture via adsorption by chitosan-based functional biomaterial: A review on recent advances, challenges, and future directions. 2023

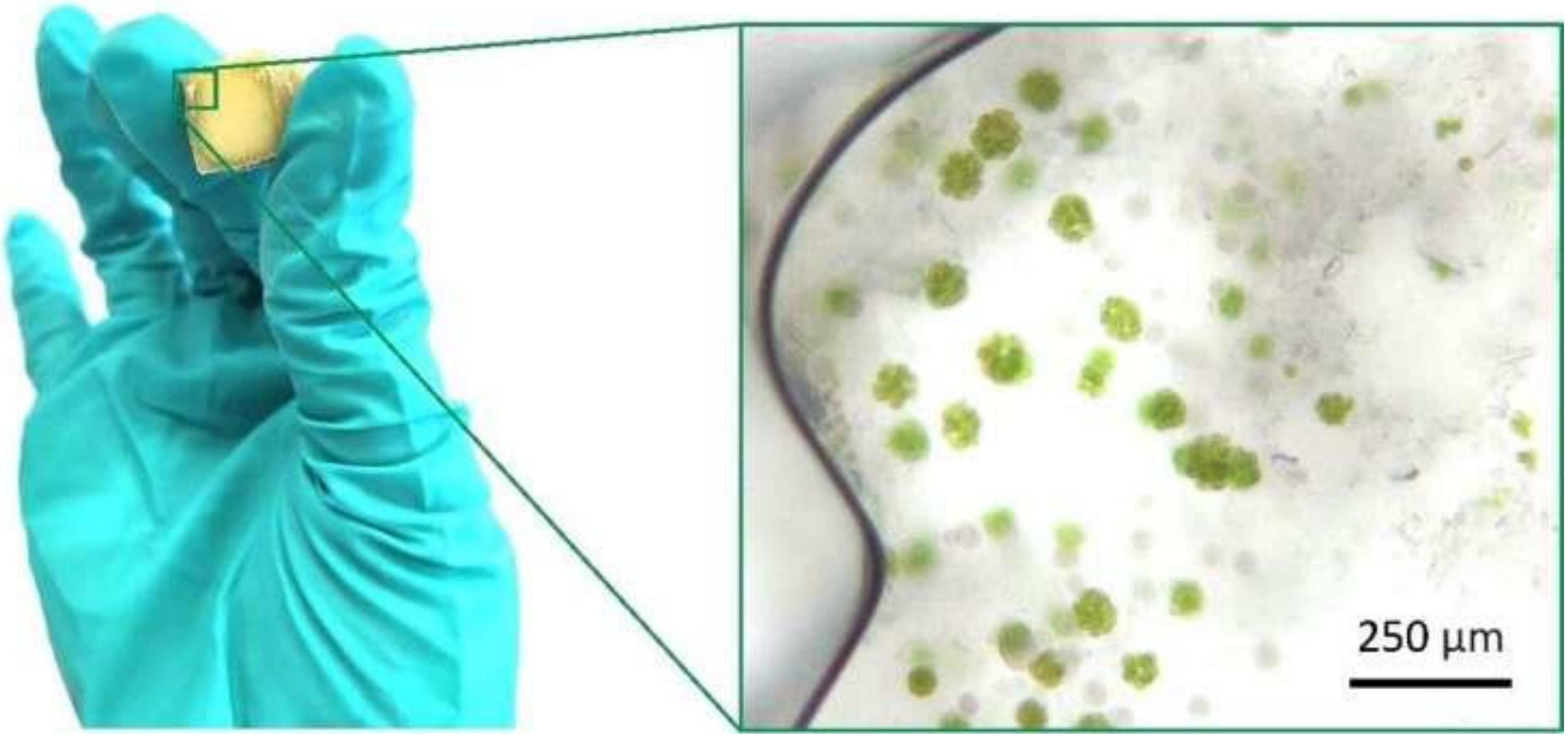
Carbon capture can occur via absorption into hemp

- The **biogenic component** of the material, hemp shivs, are 45% carbon due to the atmospheric carbon dioxide absorbed by the plant during **photosynthesis**

- The **non-biogenic component** of hemp concrete is the lime binder, engulfing hemp shivs in a hardened matrix and consuing carbon dioxide through **carbonation**

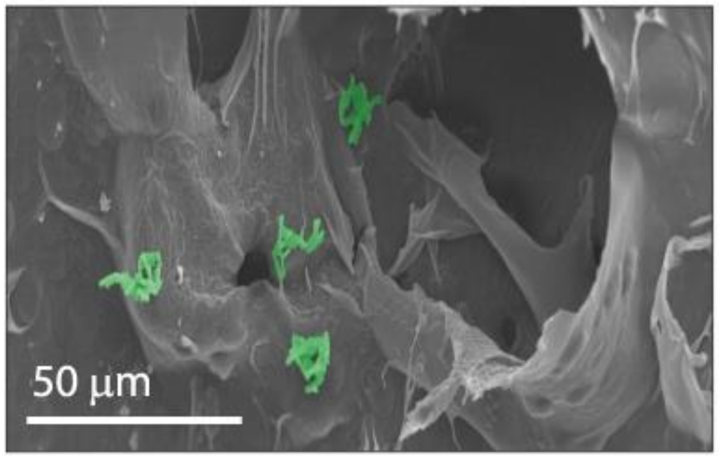


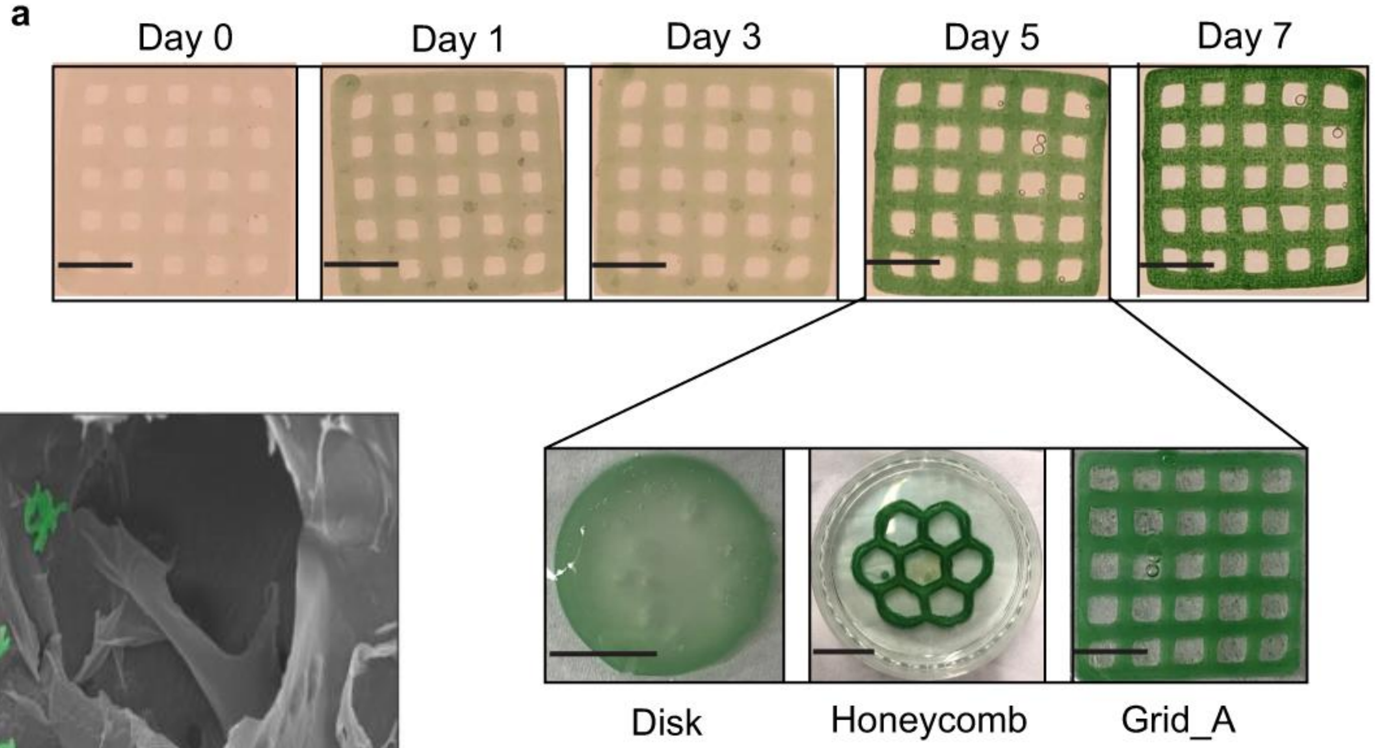
Engineered Living Materials (ELMs) can be embedded within carbon capturing organisms



Early proofs of concepts have shown successful embedding of living algae into hydrogels

- Thus far, only in aqueous conditions
- Survival only measured over 10 days (ideal survival is months - years)
- Small quantities and thin objects tested

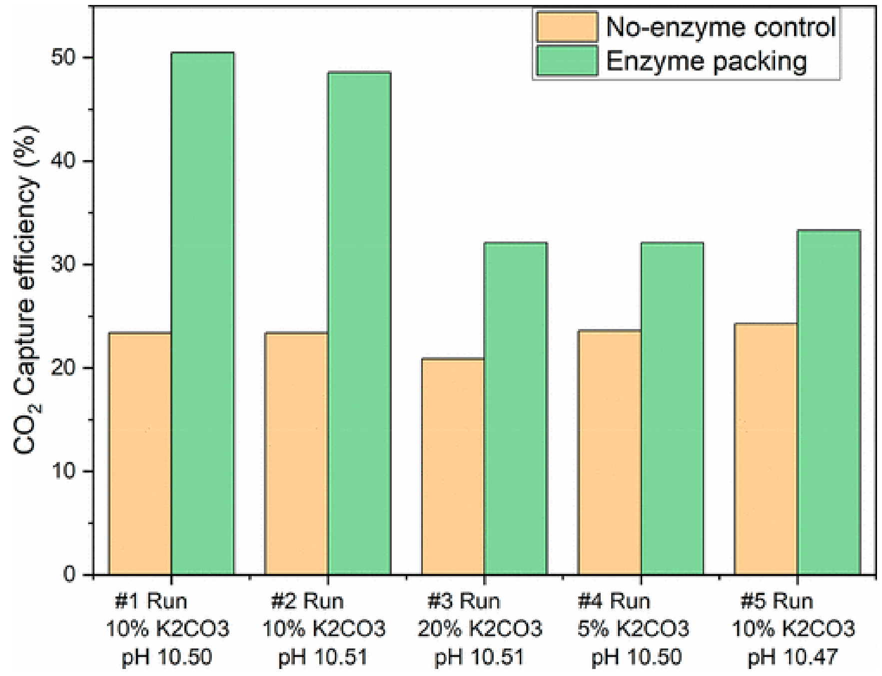




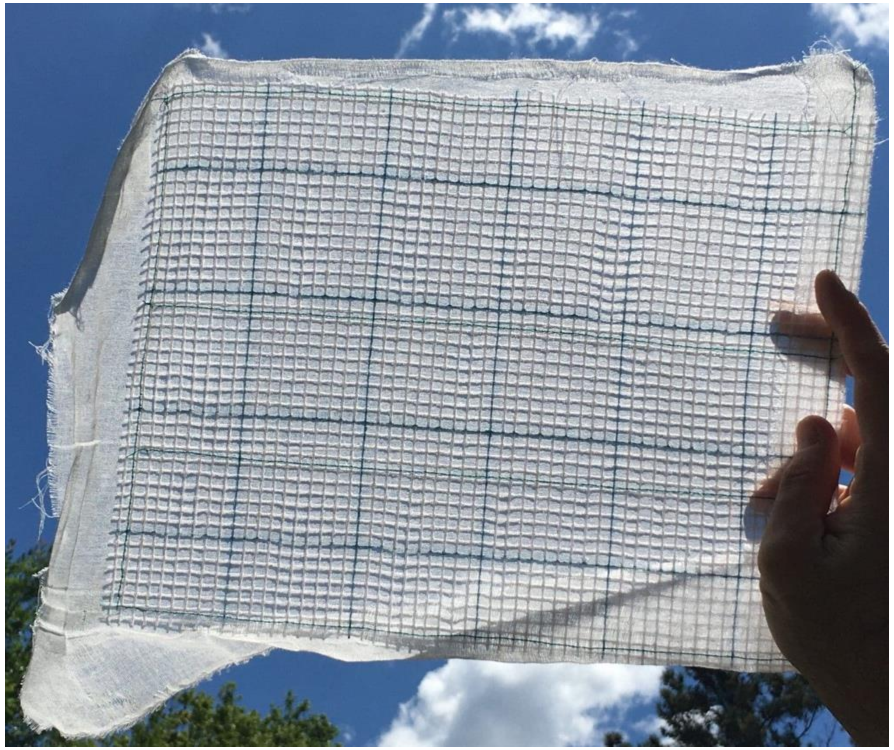
Datta et al. Phenotypically complex living materials containing engineered cyanobacteria. Nature Comunications. 2023.

Materials can be embedded with purified enzymes that sequester carbon

- **Carbonic anhydrase:** an enzyme catalyst that speeds up a carbon + water reaction resulting in bicarbonate (used in baking soda)



Shen et al. Carbonic Anhydrase Immobilized on Textile Structured Packing Using Chitosan Entrapment for CO_2 Capture. ACS Sustainable Chem Eng. 2022.

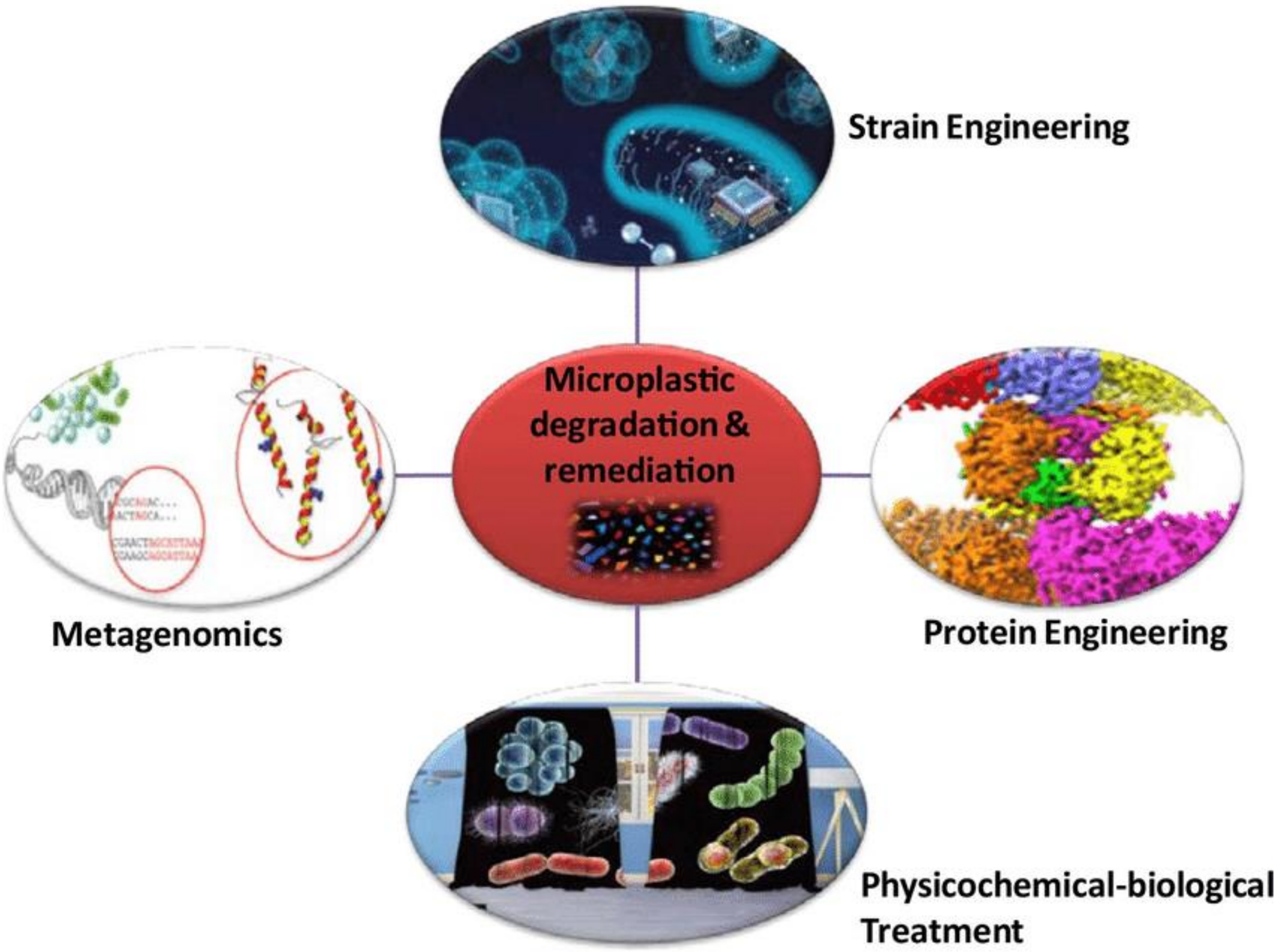


A chitosan filter embedded with carbonic anhydrase could help remove carbon dioxide from flue gas emissions and air.
Source: Sonja Salmon

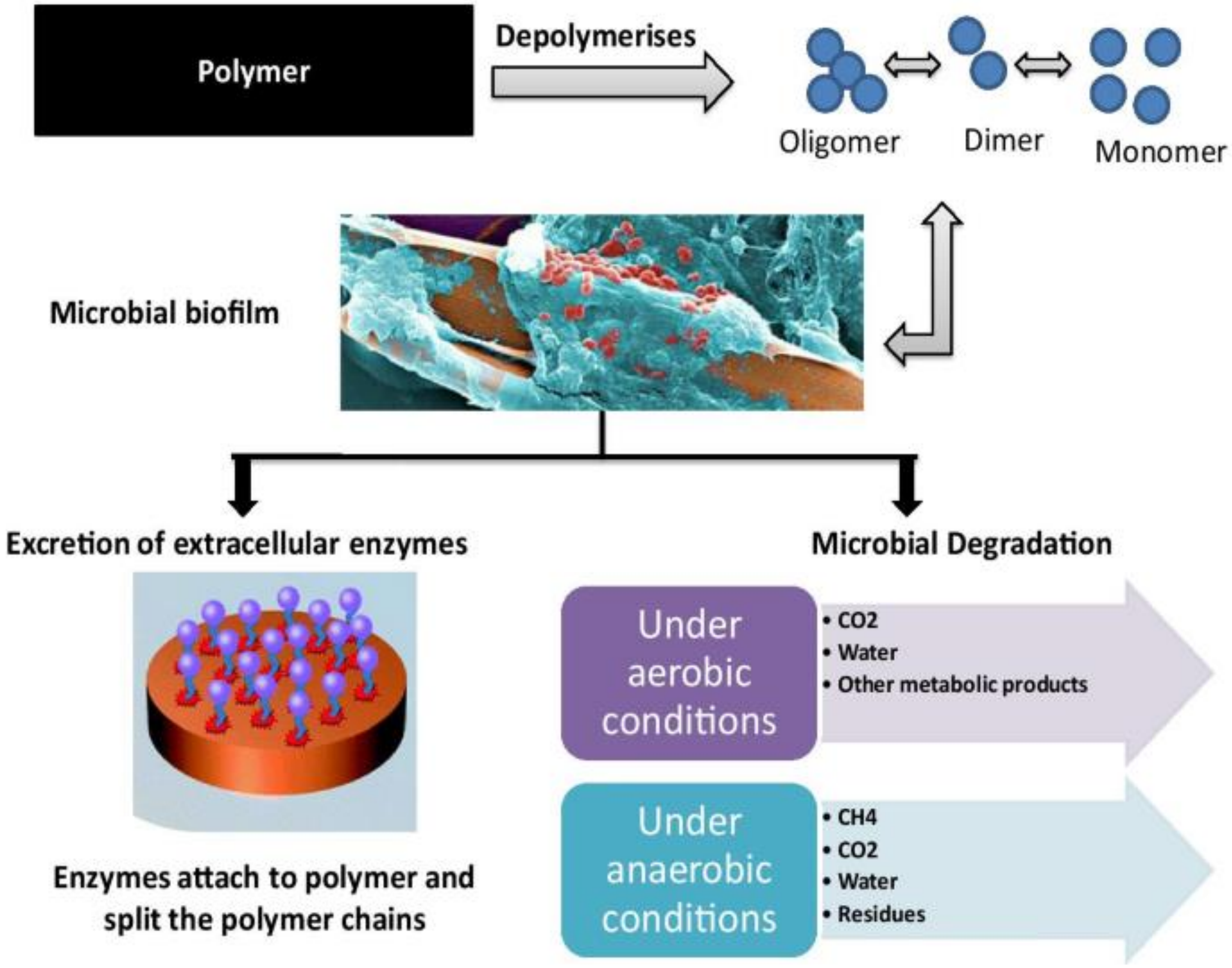
Pollution Remediation

Pollution remediation – how to deal with all the unsustainable materials already in existence?

Let's take a look at plastics specifically:

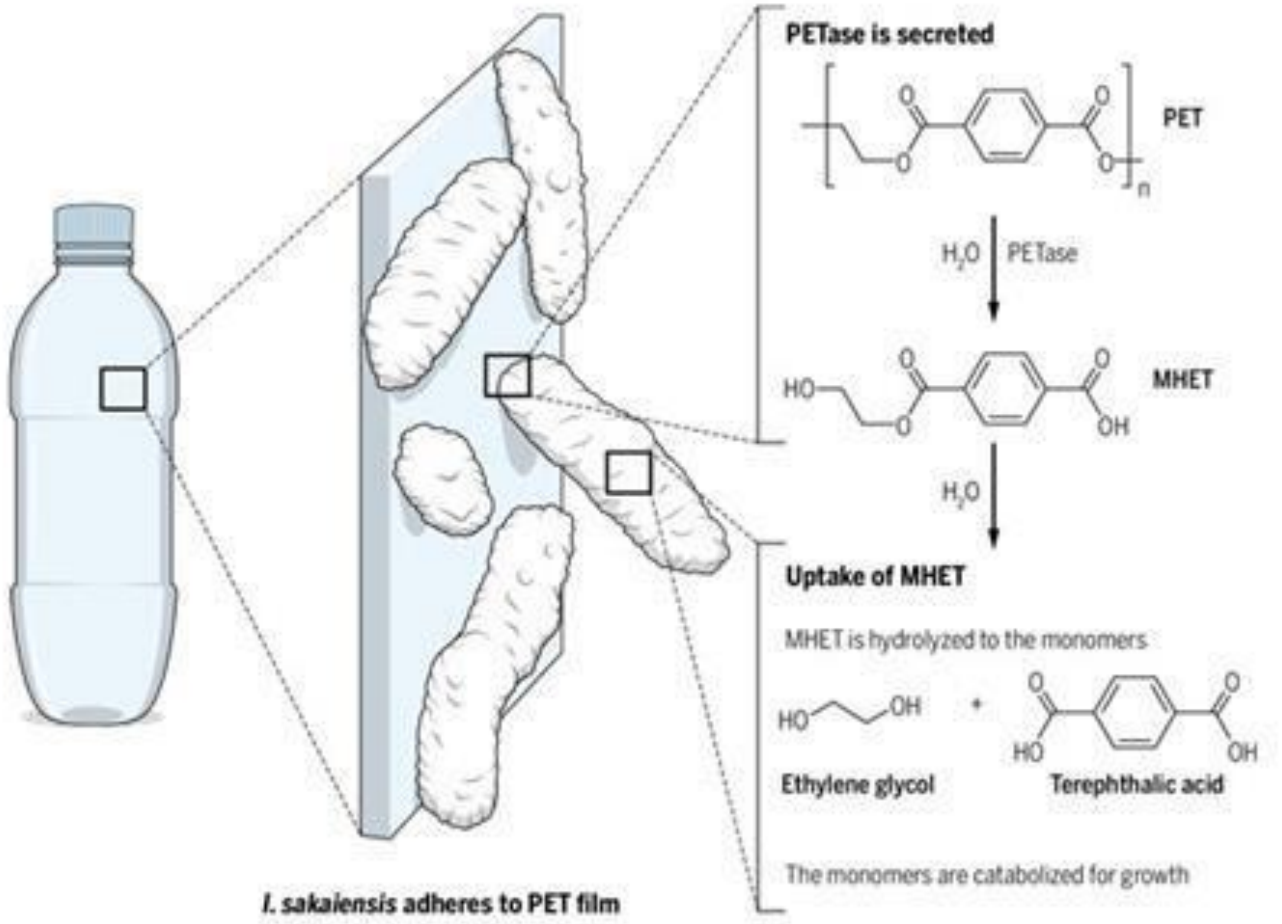


Microbial enzymes can be used to degrade plastics into monomers



Bansal et al. Behavioural Mechanisms of Microplastic Pollutants in Marine Ecosystem: Challenges and Remediation Measurements. Water Air and Soil Pollution, 2021.

Recall from last week: microbes were discovered which can degrade plastic into individual components



- Sifting through debris at a plastic bottle recycling plant has led to the discovery of microorganism that can break down polyethylene terephthalate (PET)

- **Discussion: why hasn't this technology taken off?**
  - Efficiency of the PETase
  - Stability of the PETase in different conditions
  - Ability to manufacture the PETase on a large scale

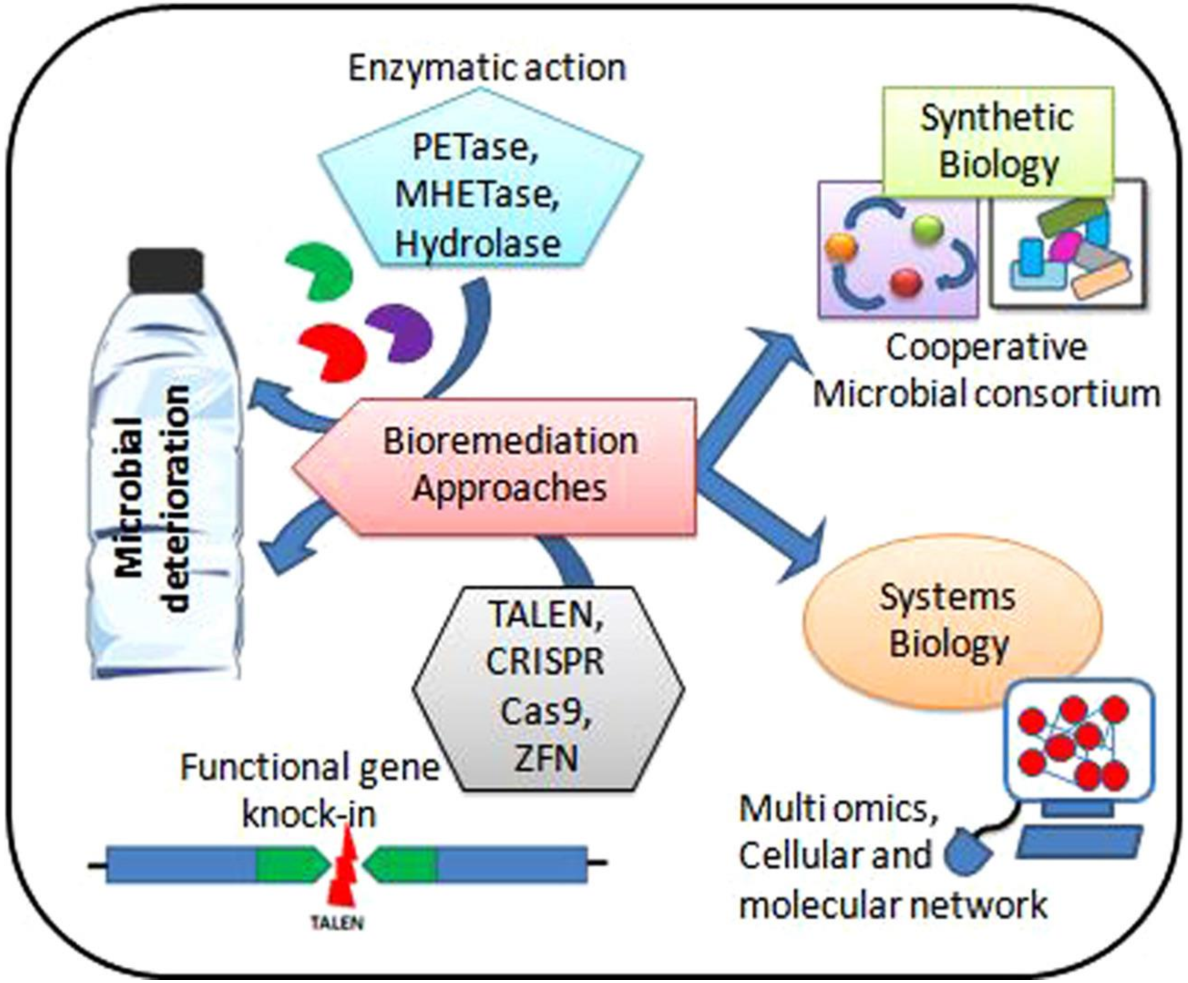
Yoshida et al. A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 2016

Strains of microbes can be **genetically engineered** to express enzymes capable of plastic degradation

- Some organisms can **exogenously produce enzymes more efficiently** than naturally evolving microbes

- Exogenous DNA can be integrated into microbes using **CRISPR-Cas9**, molecular cloning, and other methods

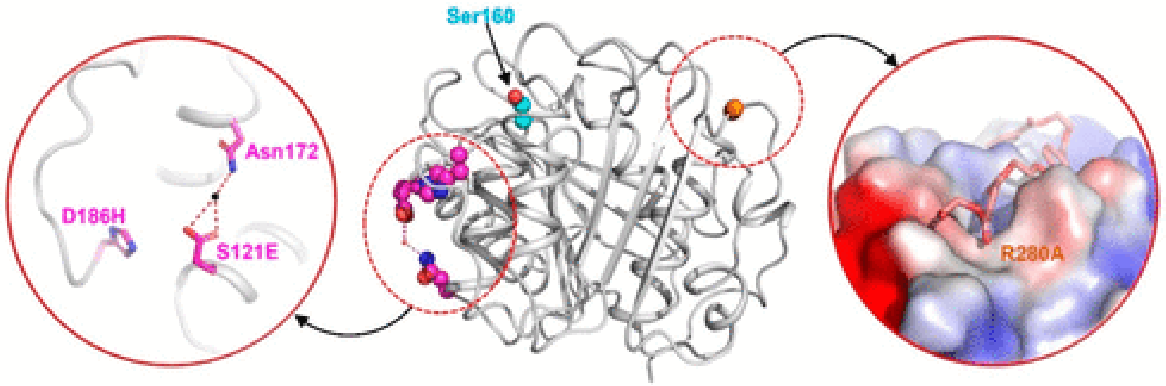
- Strain engineering is an **iterative process**

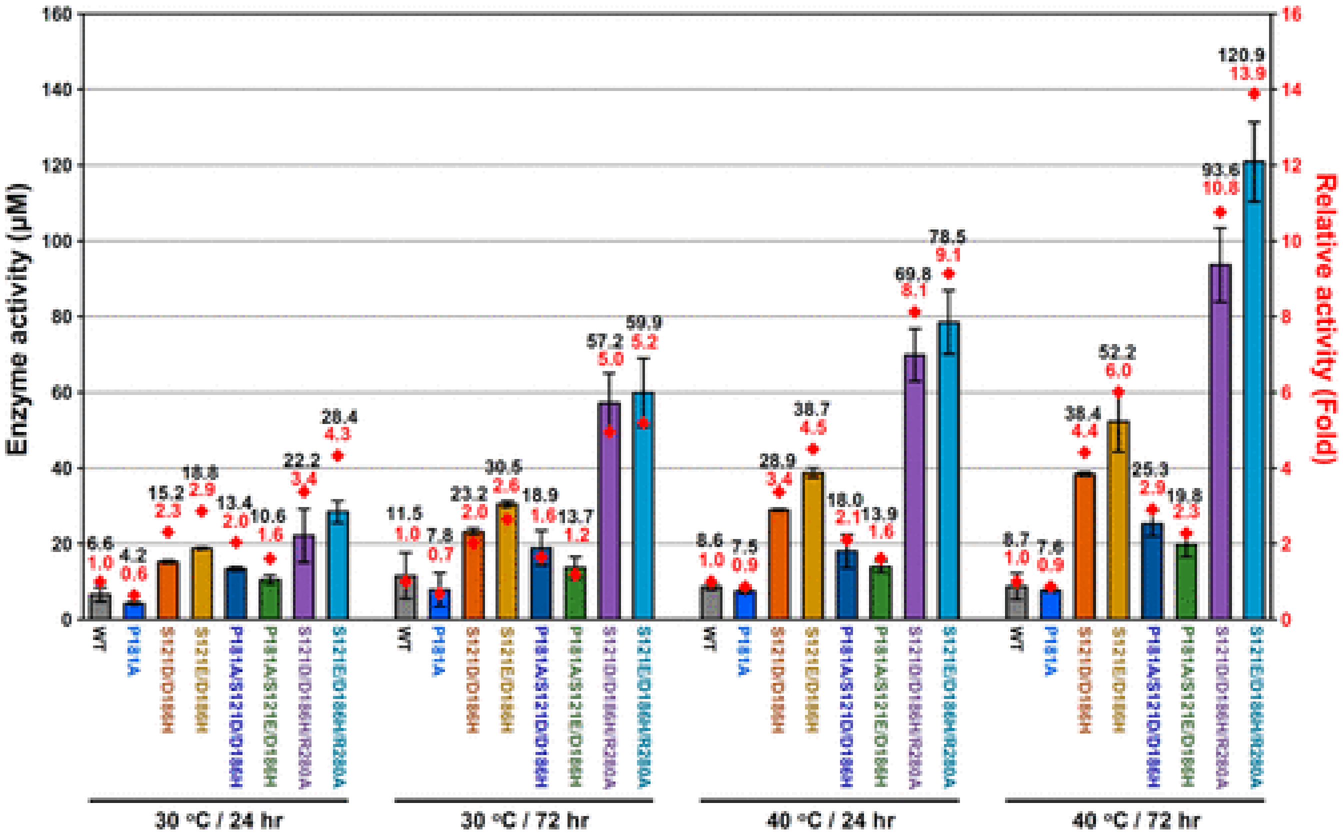


Jaiswal et al. Integrated approaches in microbial degradation of plastics Environment Technology & innovation. 2020.

Rational **protein engineering** of PETases reveals more robust enzymatic activity

- PETases have had **low degradation efficiency** due to low thermal stability
- Hypothesis: **greater thermal stability** will provide more efficient activity at diverse temperatures

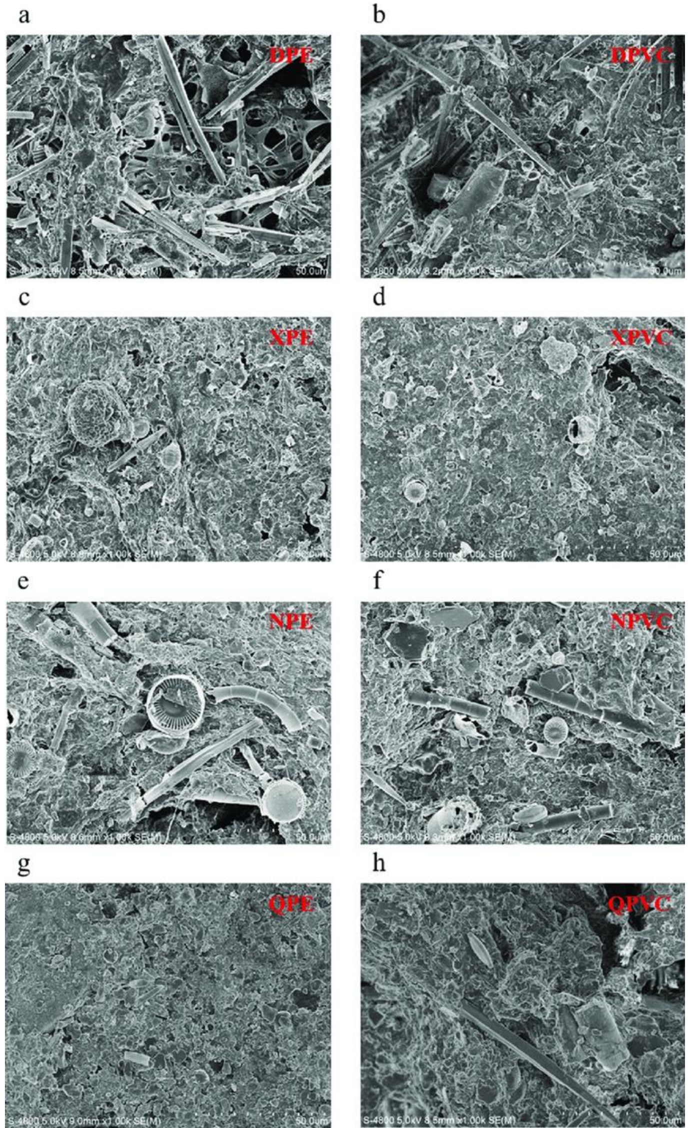




Son et al. Rational Protein Engineering of Thermo-Stable PETase from *Ideonella sakaiensis* for Highly Efficient PET Degradation. ACS Catalysis. 2019

Metagenomic analyses of biofilms formed on plastic can reveal distinct pathways necessary

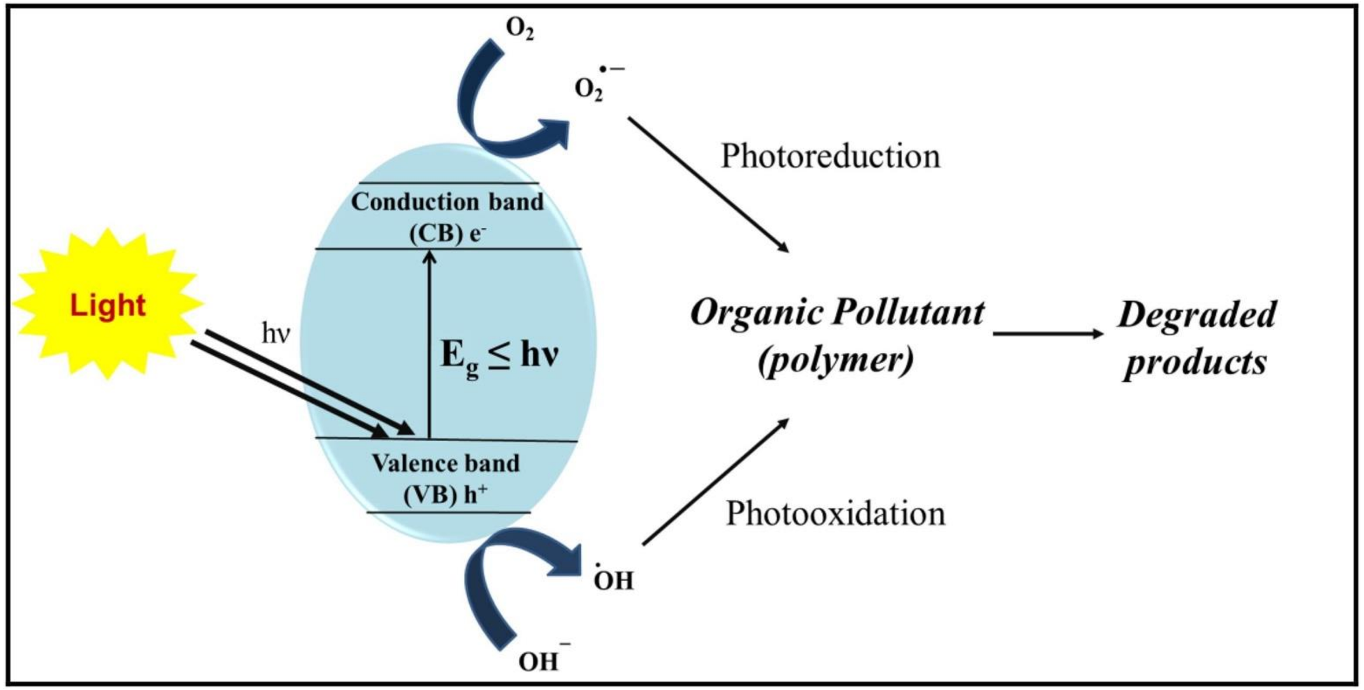
- **Metagenomic sequencing:** study of the function of entire DNA sequences isolated from all the organisms in a **bulk sample**
- Used for studying **distinct microbial profiles** within biofilms
- Metagenomic datasets can reveal trends across many enzymes present which can **inform protein engineering strategies**



Miao et al. Microbial carbon metabolic functions of biofilms on plastic debris influenced by the substrate types and environmental factors. Environment International. 2021.

Physico-chemical- biological treatment combination can speed up process

- Combining **biological treatment** with **chemical treatments** to speed up the process
- For example: **UV-radiation** or **ozone pre-treatment** to break apart large pieces, followed by incubation of microplastics with plastic-degrading bacteria



Sharma et al. Microplastics in the environment: Occurrence, perils, and eradication. Chemical Engineering Journal. 2021

Discussion section (~15-20 mins)

- Pre-work: Watch Suzanne Lee's Ted Talk on Youtube "Why "biofabrication" is the next industrial revolution" from 2020

- Form groups of 3-4 people and go over the following questions together (10 mins)
  - Do you think that biofabrication is feasible? Why or why not?
  - Why is biofabrication more popular now? What technologies have enabled it?
  - What are the current obstacles for biofabricated materials?
  - What steps need to be taken to move towards a biofabricated world?

- Let's discuss as a group (5-10 mins)

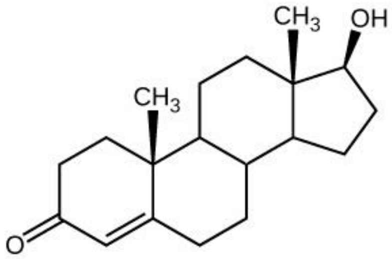
Biomanufacturing

Biomanufacturing is the cultivation of cells to make a higher value ingredient or material

Proteins

Sugars

Hormones

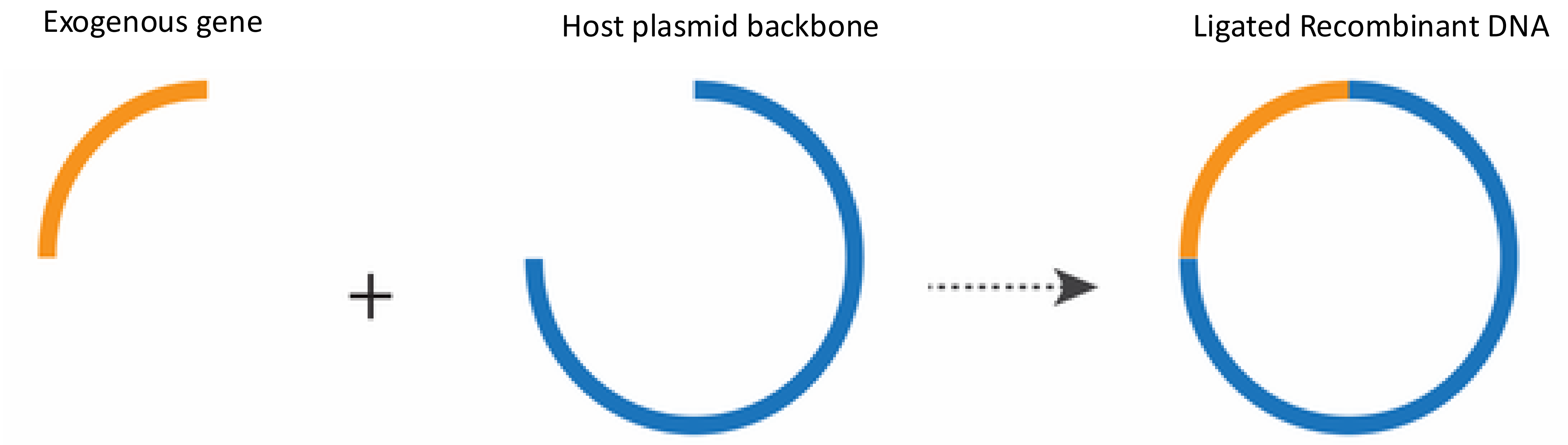


Lipids

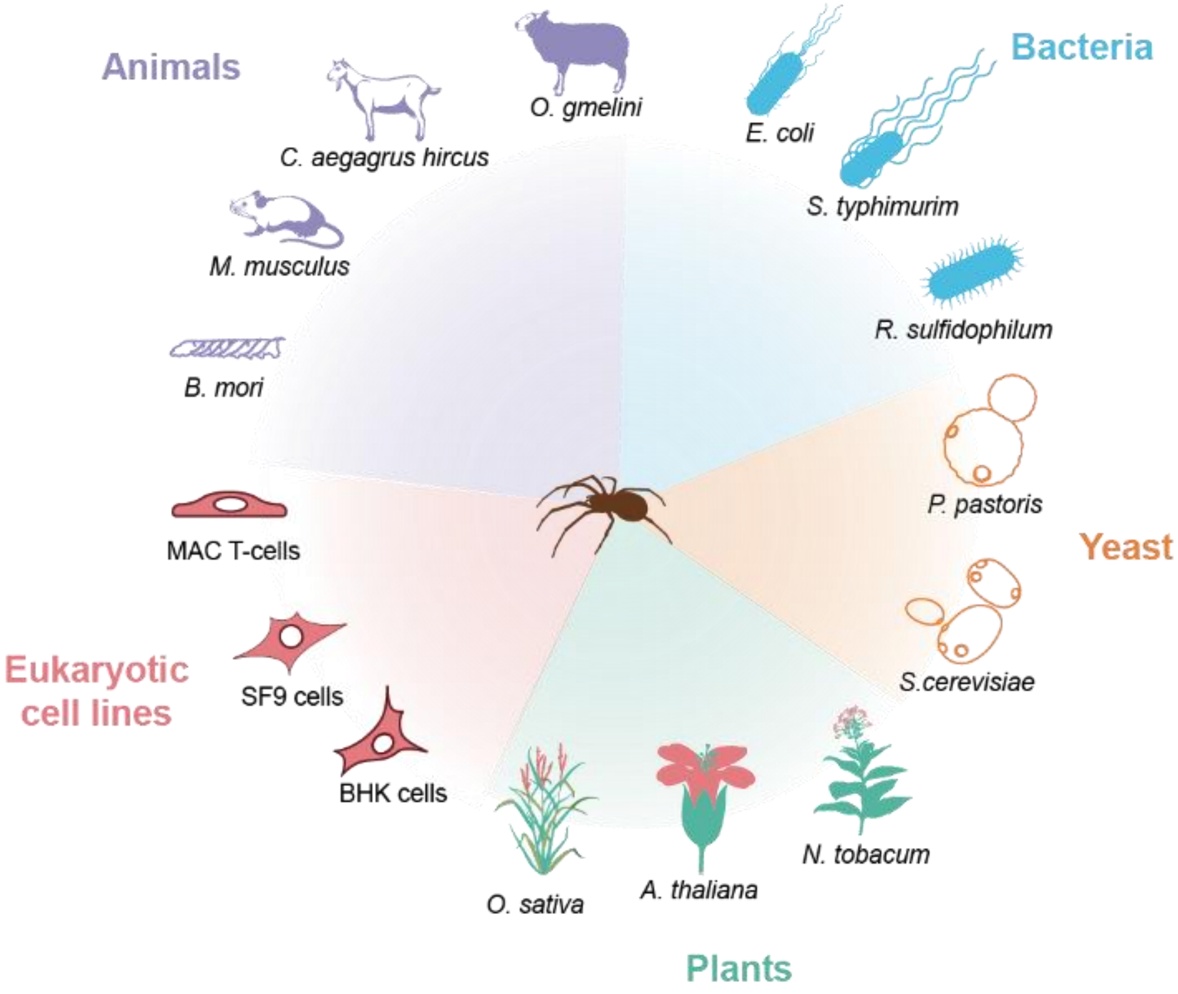
Biofuels

Bioplastics

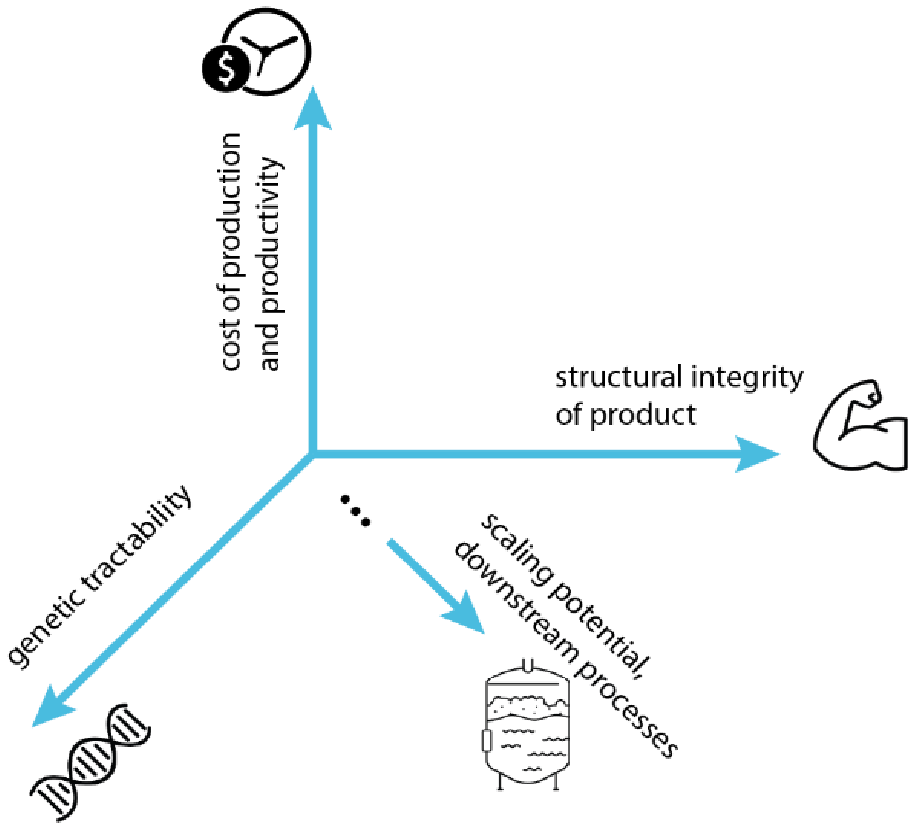
Biomanufacturing typically involves expressing recombinant genes exogenously in host microbes



Biomanufacturing can take place in a variety of hosts with unique advantages

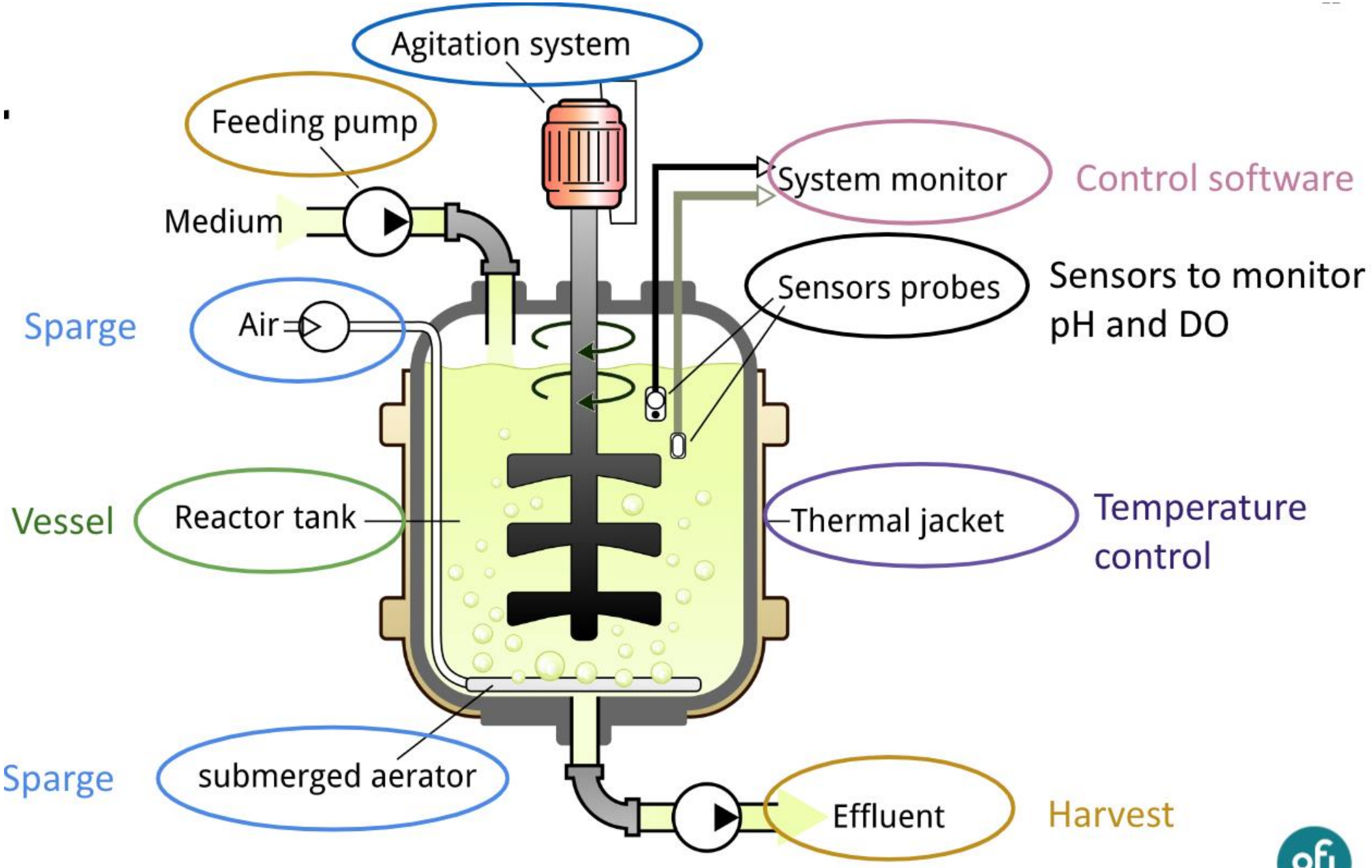


When choosing a host organism, scale-up potential is just one of many considerations



A fermentor/bioreactor must maintain the right pH, temperature, air flow, nutrients, and movement

- **Culture medium** contains a carbon source (such as glucose, glycerol, or cellulose), amino acids, and salts



Scaling up is moving from lab testing to demo scale, to pilot/commercial scale

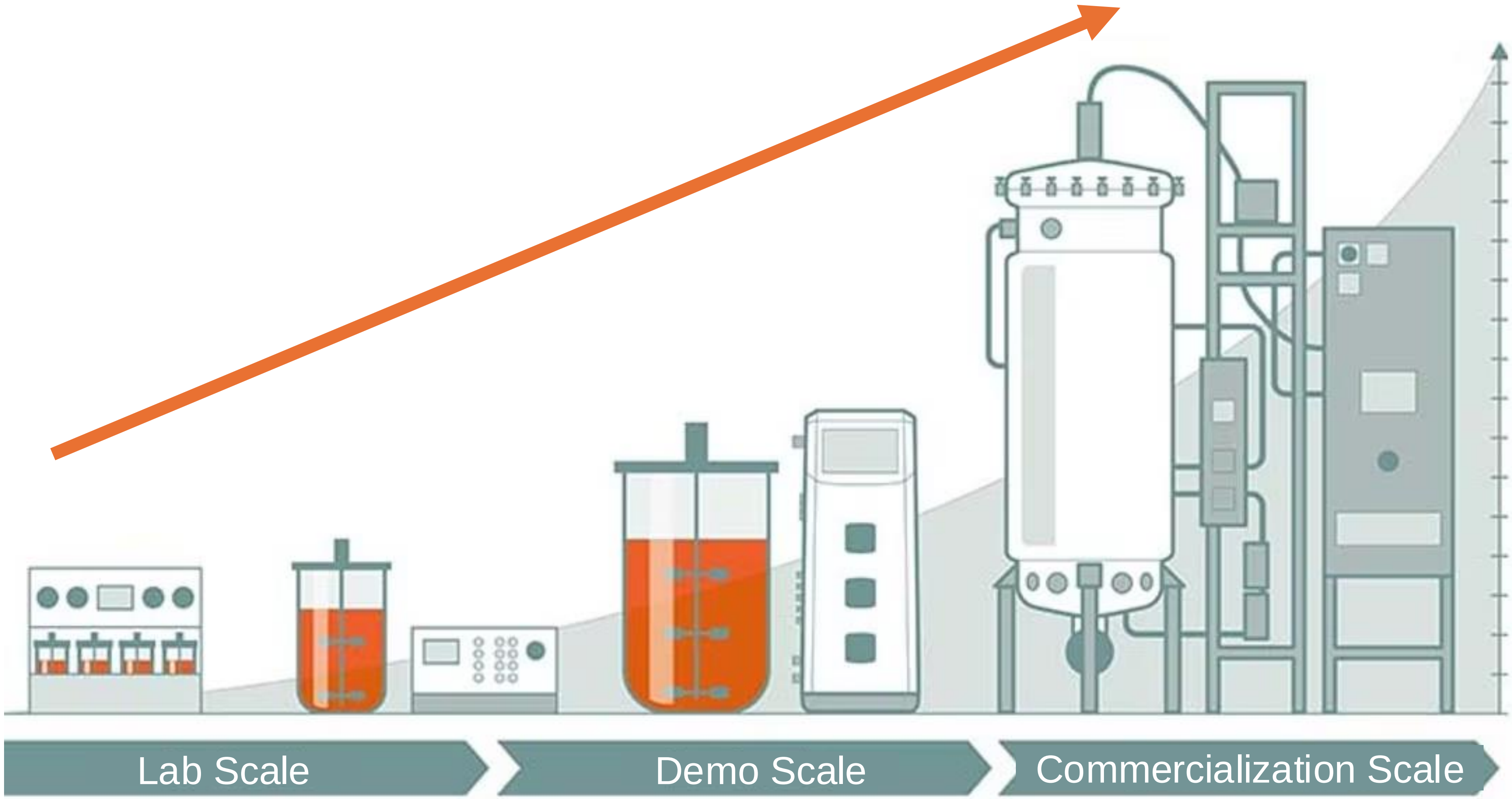
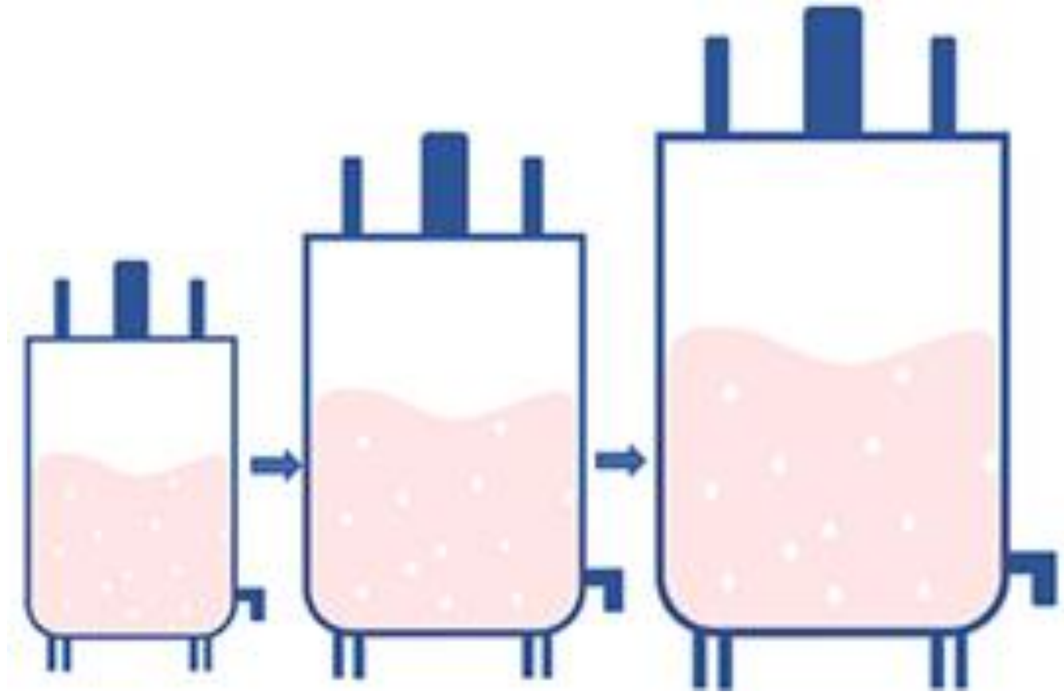


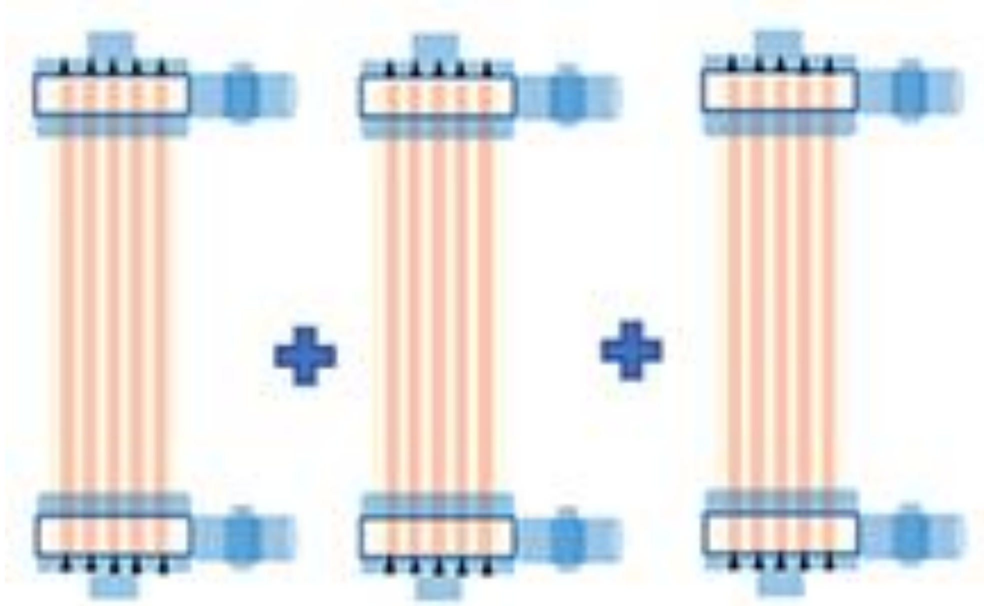
Figure by: Eppendorf.com

Scaling out is another strategy for increasing biomanufacturing production

Scale-up: Bioreactors increase in volume to enable more production

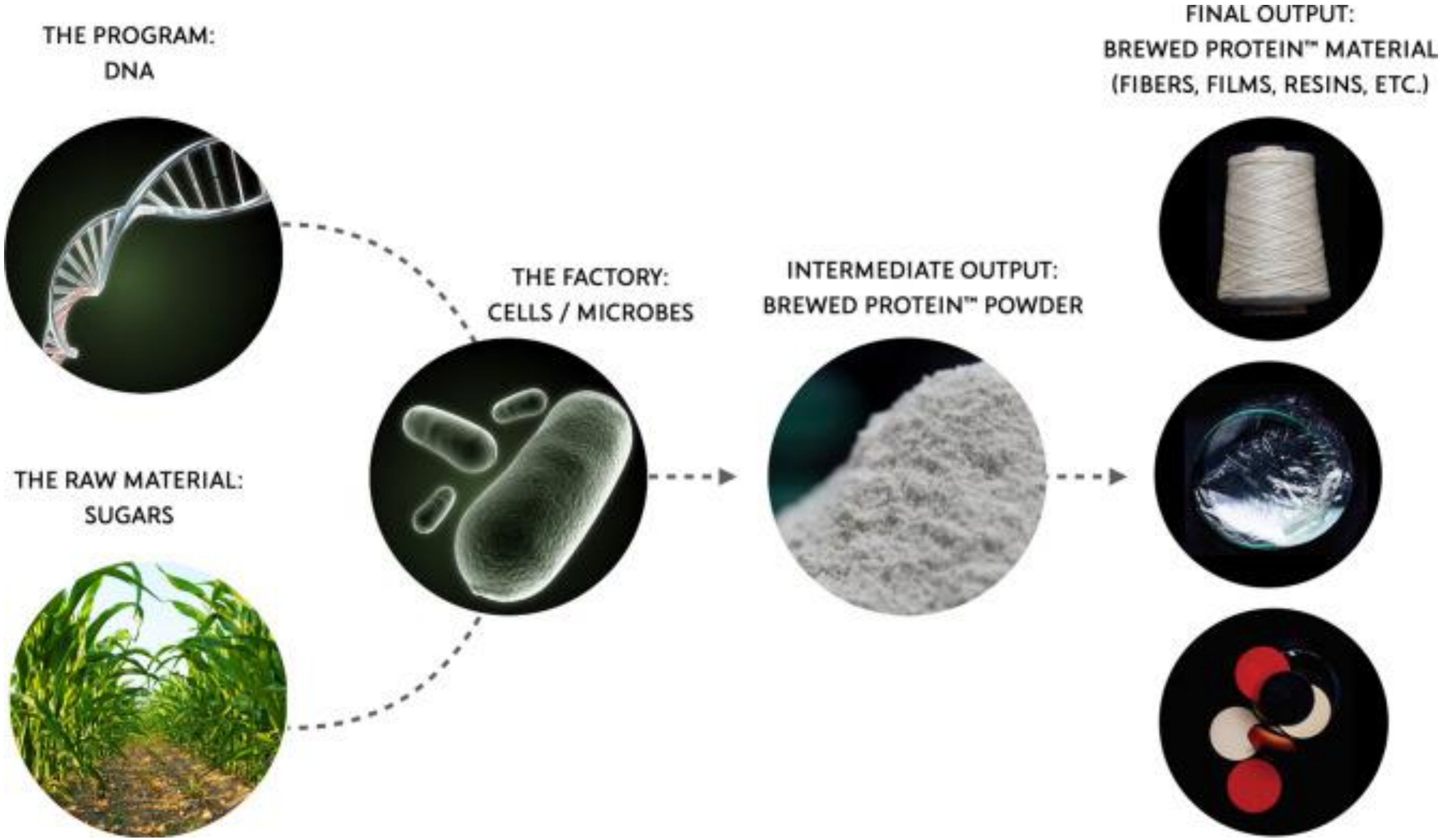


Scale out: bioreactors stay at smaller volumes, but the number of bioreactors used in a manufacturing run multiplies.



Graphics by PharSol

Example of biomanufacturing: spider silk gene grown in bacteria can produce many protein-based products

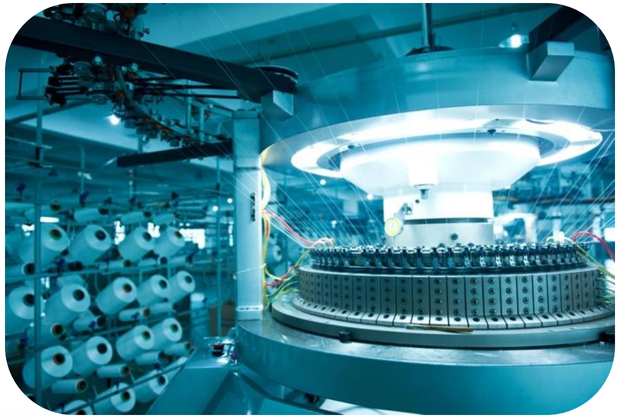


Photos of Spiber Inc's Brewed Protein™

Molecular farming in plants is another promising biomanufacturing alternative

SPIDEY TEK

They also tried:



- According to the CEO of Spidey Tek, the sale of alfalfa to the agricultural industry **offsets 100% of the production costs** of the spider silk

Feedstocks lignocellulosics- what to do with all this lignin??

- Engineering of cells to metabolize lignocellulosic

There are many diverse career opportunities within sustainable material innovation

Advocacy via non-profit organizations

MATERIAL INNOVATION INITIATIVE

gfi Good Food Institute

Consulting

BIOFABRICATE

HELIKON CONSULTING

Academia (PhD, post-doc, professor)

Tufts UNIVERSITY

Government Policy

U.S. DEPARTMENT OF ENERGY

EPA

NSF U.S. National Science Foundation

Entrepreneurship

hempitecture

Breakthrough Energy

Y Combinator

Galy

Industry

Seventh Generation

the hemp crete co.

Spiber

GINKGO BIOWORKS THE ORGANISM COMPANY