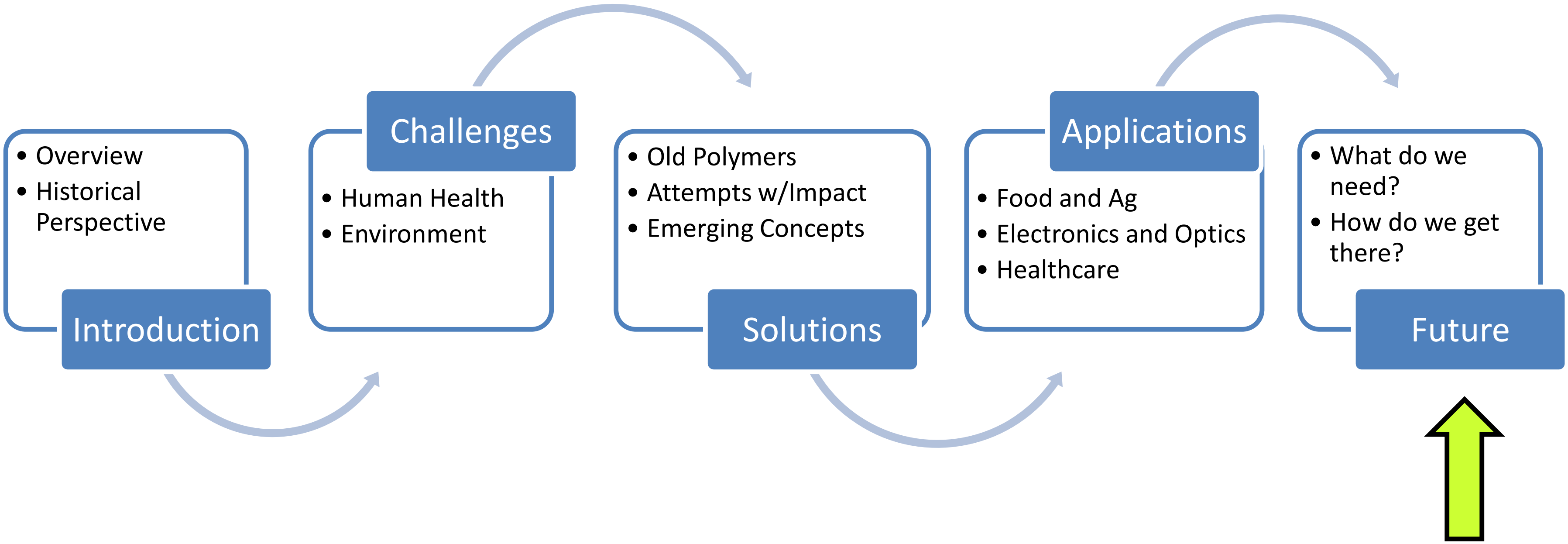
Sustainable Materials

Fall, 2024

The Future

- challenges
- opportunities

Course Overview



Introduction
- Overview
- Historical Perspective

Challenges
- Human Health
- Environment

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?

Today & Tomorrow ……

Get Involved !!!

- here at Tufts
- beyond Tufts
- research, write, communicate, vote
- development
- activism
- behind the scenes or in the scenes
- be active not passive

The Future:

Sustainable materials as materials

Sustainable materials for food

Modeling and simulation

Synthetic biology

Reminders for inspiration

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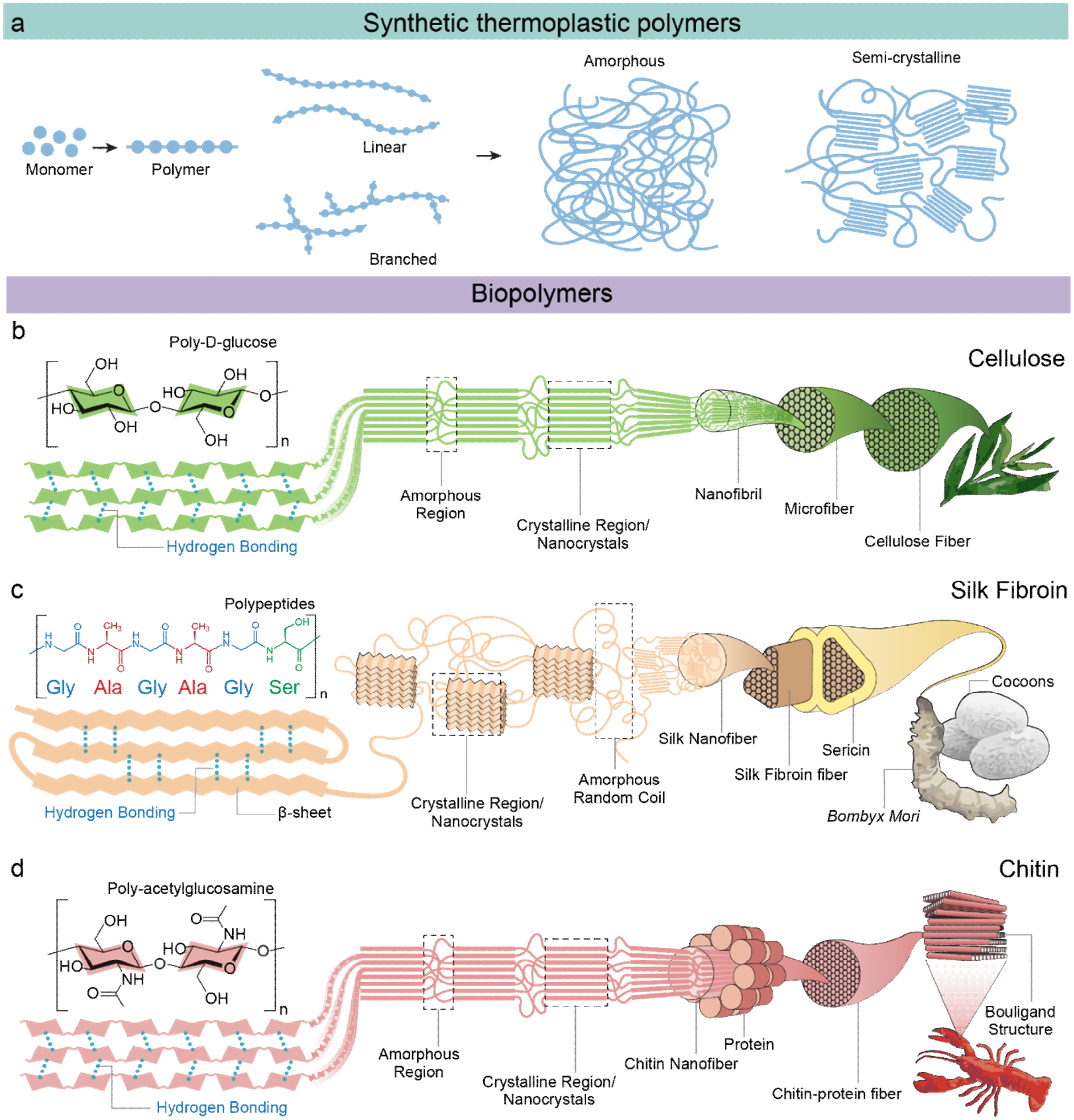
Reminders for inspiration



Sustainability

Some of the most dominant biopolymers on earth are sustainably produced

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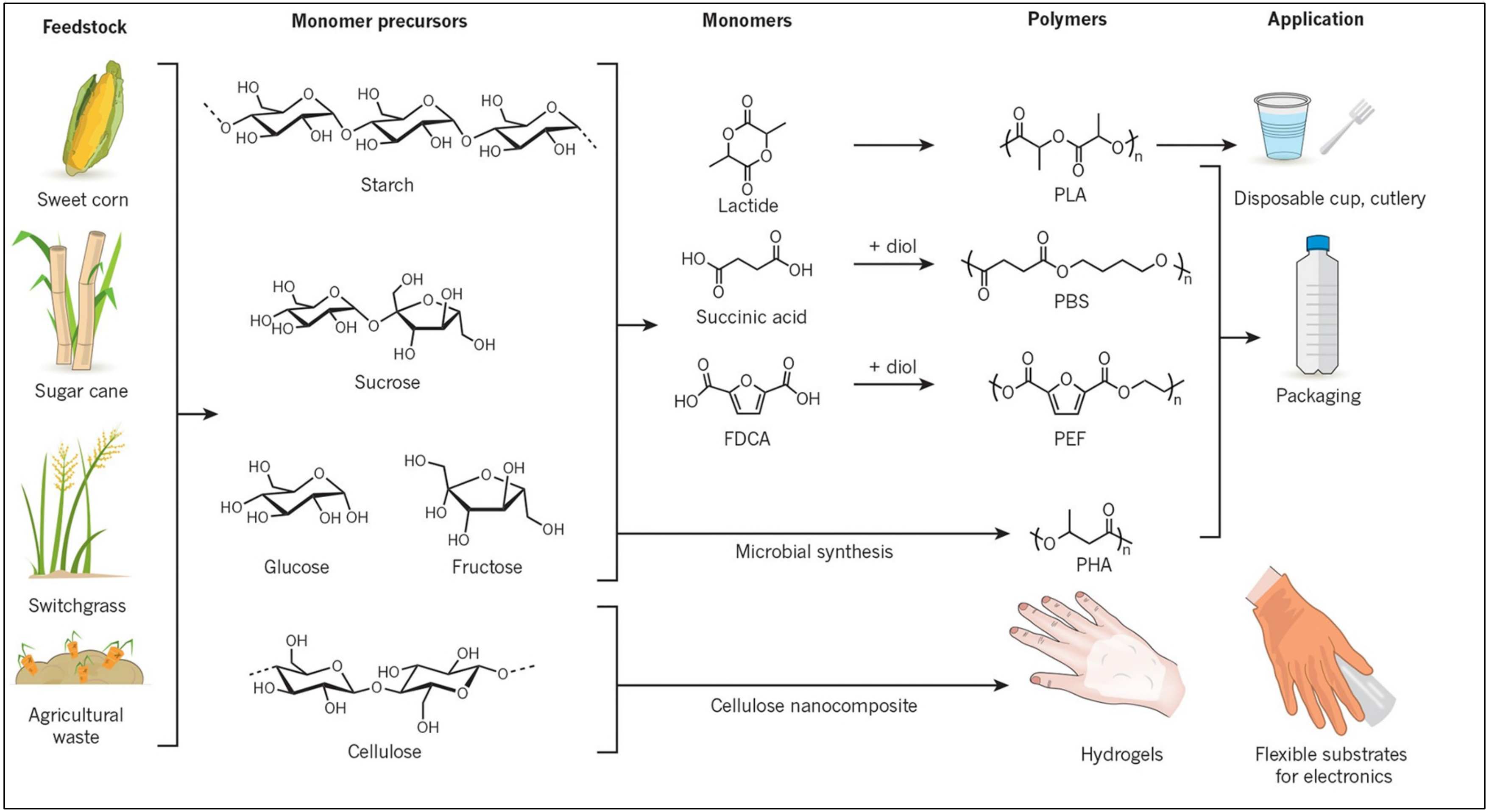
no glues

no covalent bonds between chains

no chemical crosslinkers

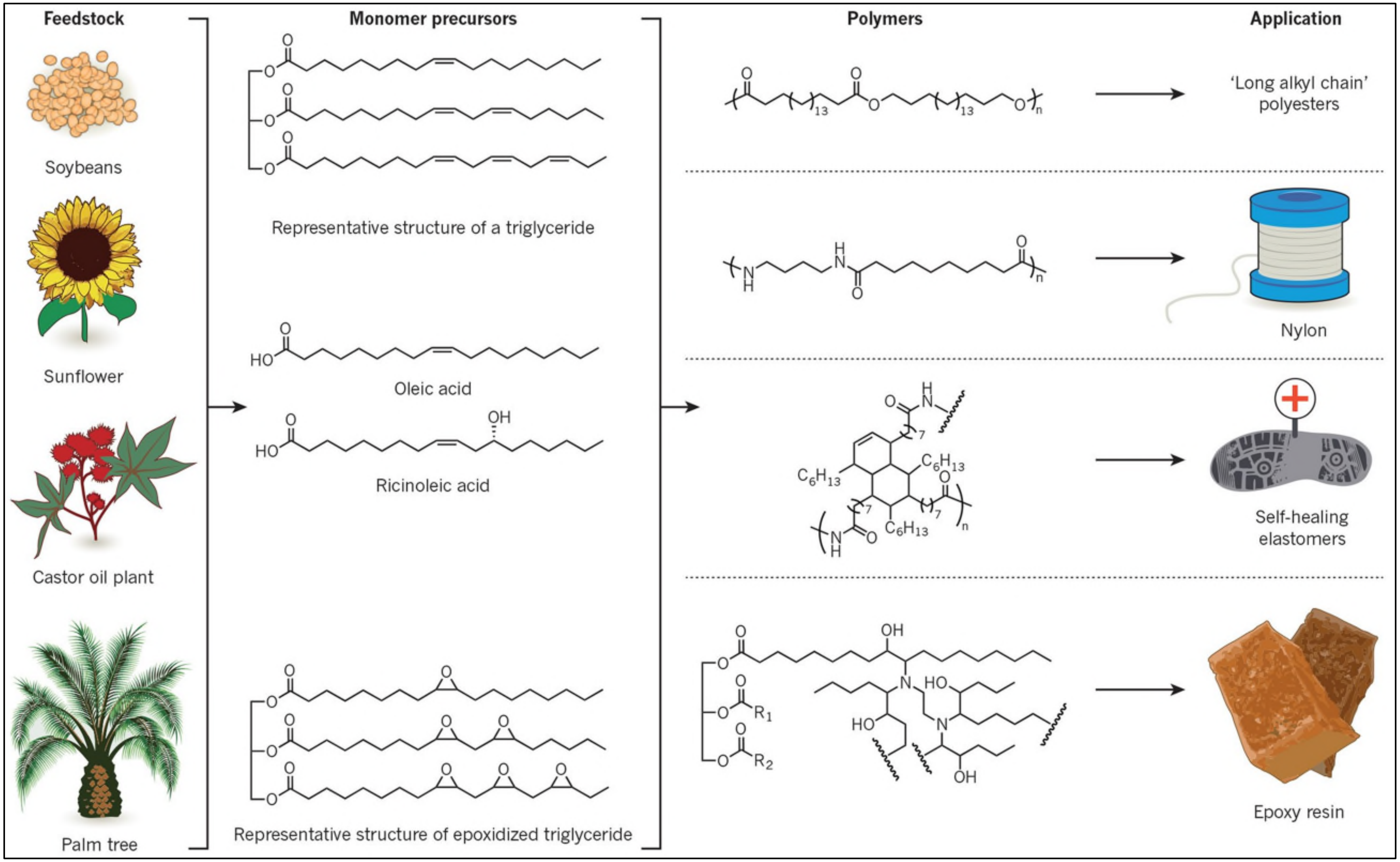
Ling et al., ***Nature Reviews Materials***, 2019; Li et al., ***Advanced Matls***., 2021

Sustainable polymers produced from polysaccharides

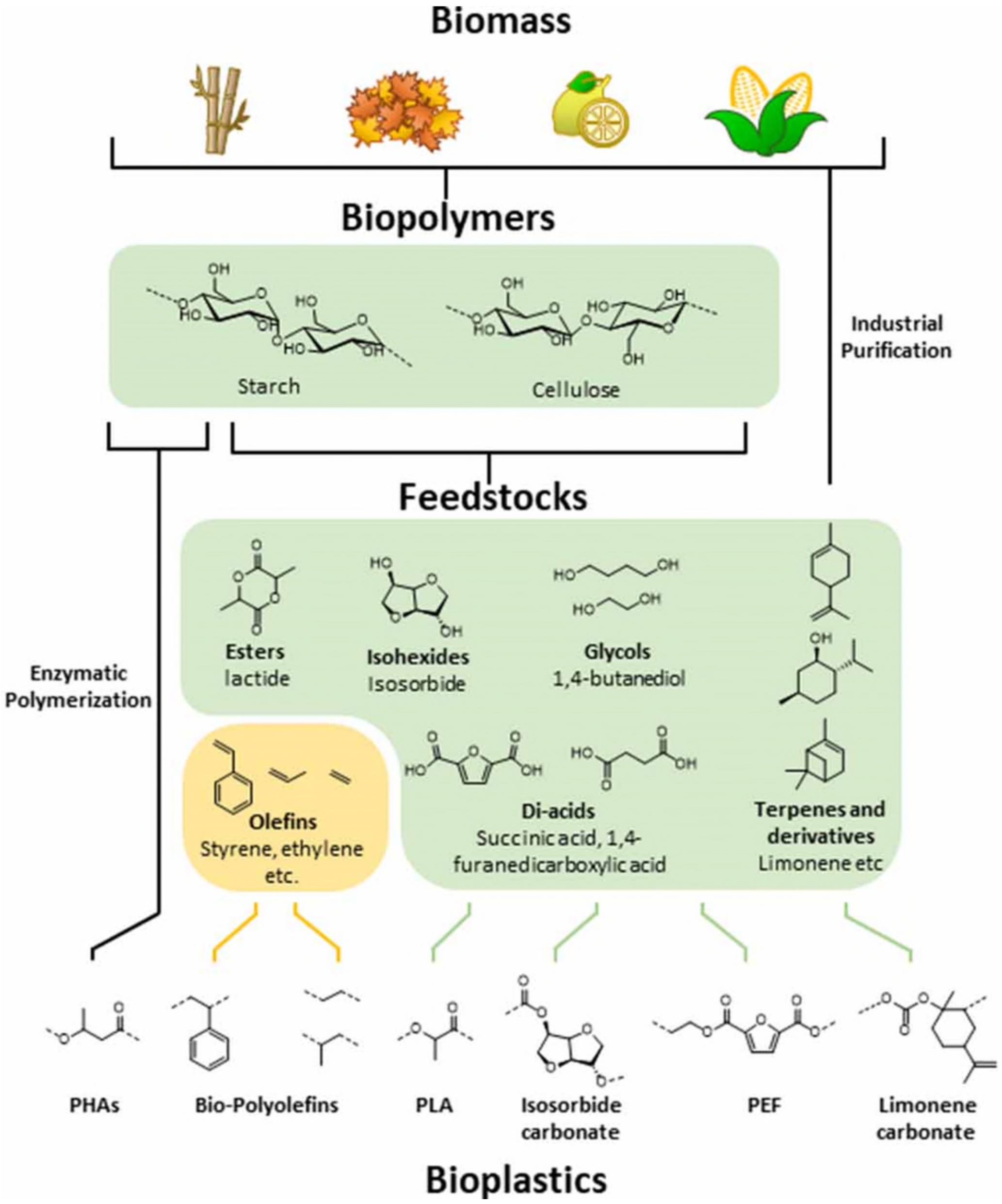


Plants such as sugar cane and maize are good sources of sucrose or starch, transformed to monomers, including lactide, succinic acid, 2,5-furandicarboxylic acid (FDCA) - monomers polymerized to polylactide (PLA), poly(butylene succinate), poly(ethylene furanoate) (PEF). Poly(hydroxyalkanoate) (PHA) produced directly from glucose by biosynthesis. Cellulose fibers to reinforce composites for hydrogels or flexible substrates for electronics.

Sustainable polymers produced from vegetable oils



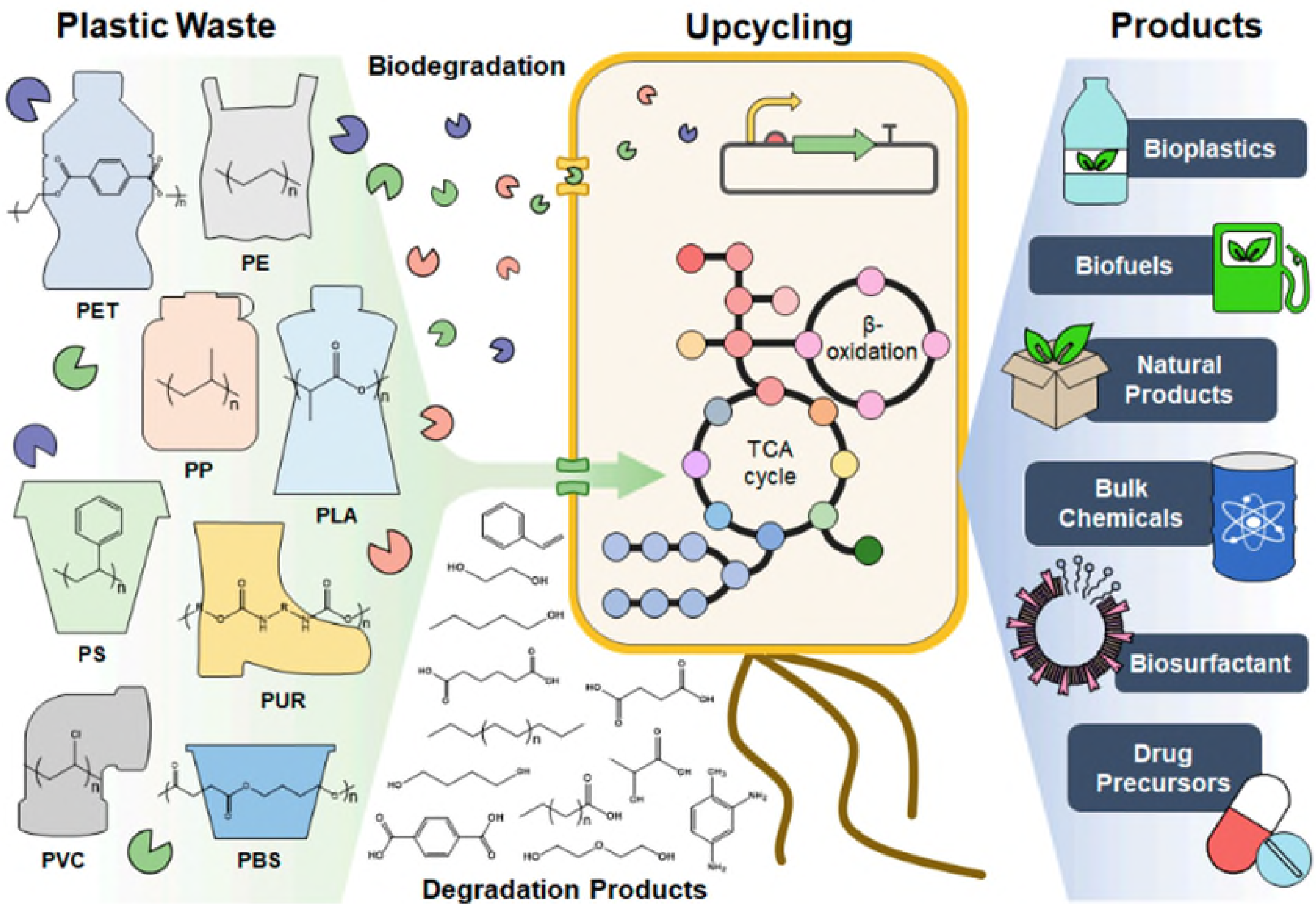
Plants such as soybean, sunflower, castor oil or palm tree are good sources of triglycerides - triglycerides transformed to polymers such as polyesters or nylons and are subsequently applied as elastomers or resins



bioplastics (BPs) production

including synthetic polymers with novel compositions from biomass feedstocks

These papers are a dime a dozen…so why do we still struggle with plastic waste?



Lee G.H., Kim D.W., et al. *Int. J. Mol. Sci.* **2023**, *24*(20), 15181

metabolites and **biopolymers from nature – many places to look, data mine, isolate, study, utilize…**

Examples:
- pigments
- structural proteins
- cellulose
- hormones
- plastics

Beta carotene, biosynthesized by algae

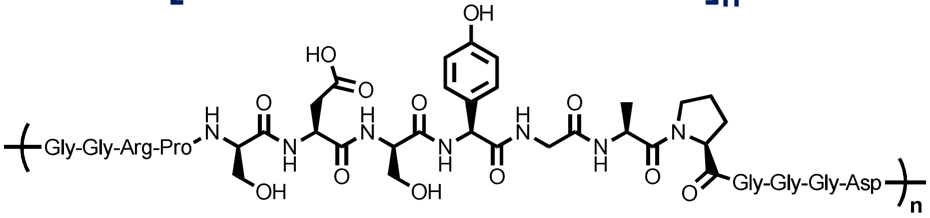
Fiber structural organization in cellulose film

Fibrous Proteins in Nature - tough materials & building blocks

Resilin

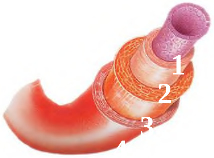
- Elastomer
- Energy storage
- Tyrosine cross-links, controllable

[GGRPSDSYGAPGGGN]$_n$



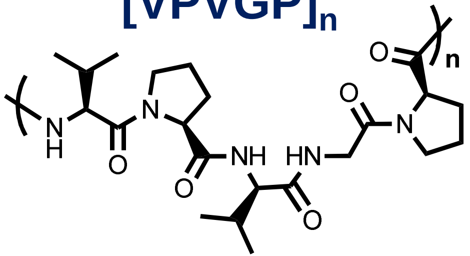
Qin et al., *Nature Comm.*, 2012

Elastin



- Elastomer
- Inverse temperature transition, controllable (temp, pH, etc.)

[VPVGP]$_n$

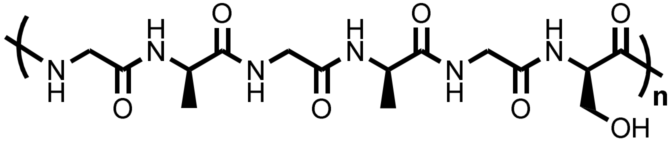


Hu et al., *Biomaterials*, 2011

Silks

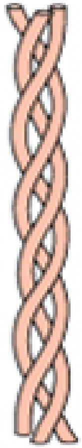
- Tough material
- Physical cross-links

[GAGAGS]$_n$



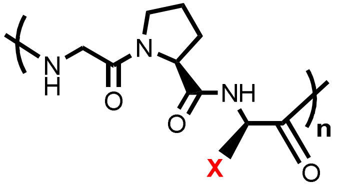
Omenetto and Kaplan, *Science*, 2010

Collagens



- Structural hierarchy
- Cell signaling
- Thermal transitions

[GPX]$_n$



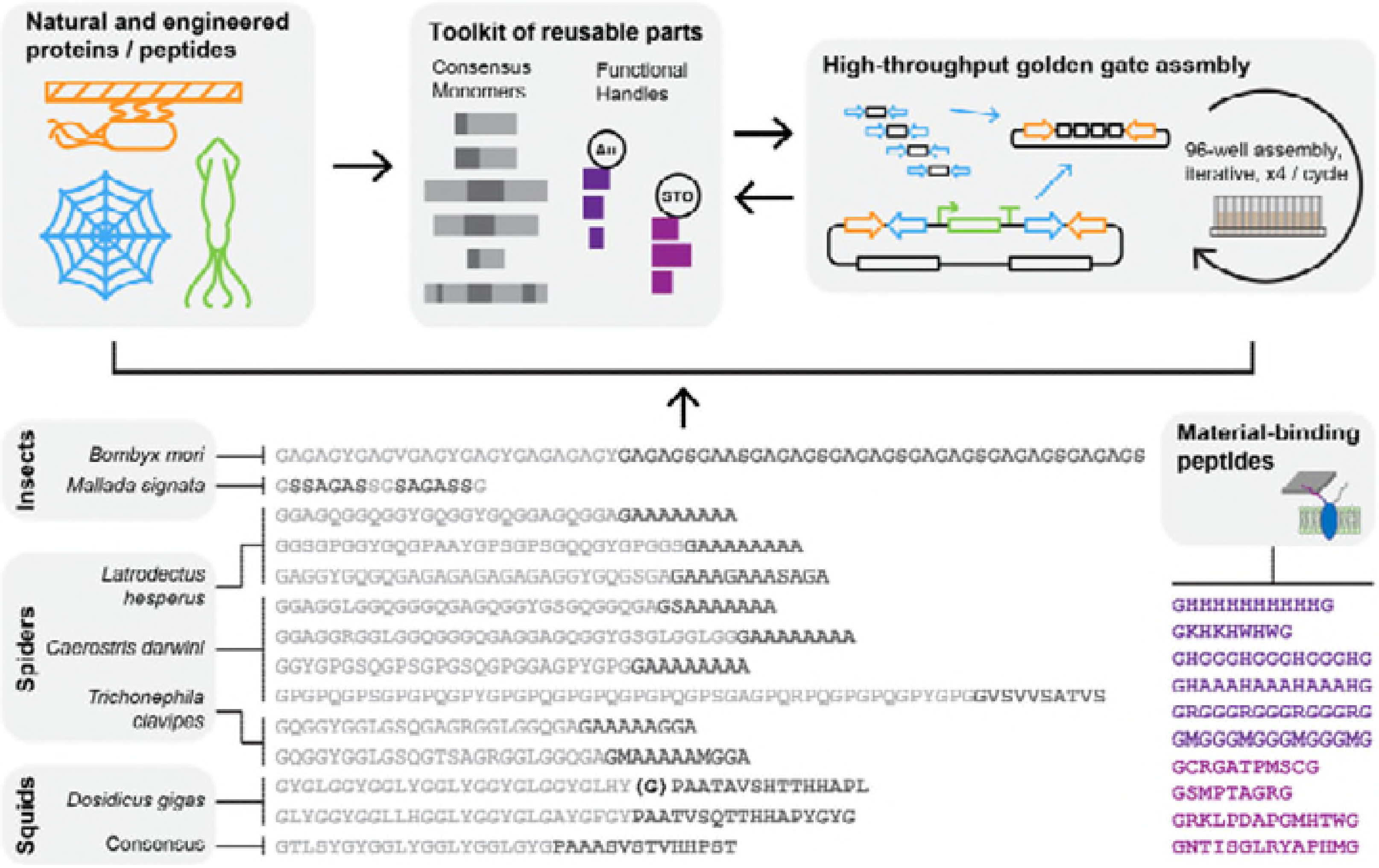
An et al., *Biomaterials*, 2012

Keratins

hair nails
scales
feathers
horns
claws
hooves

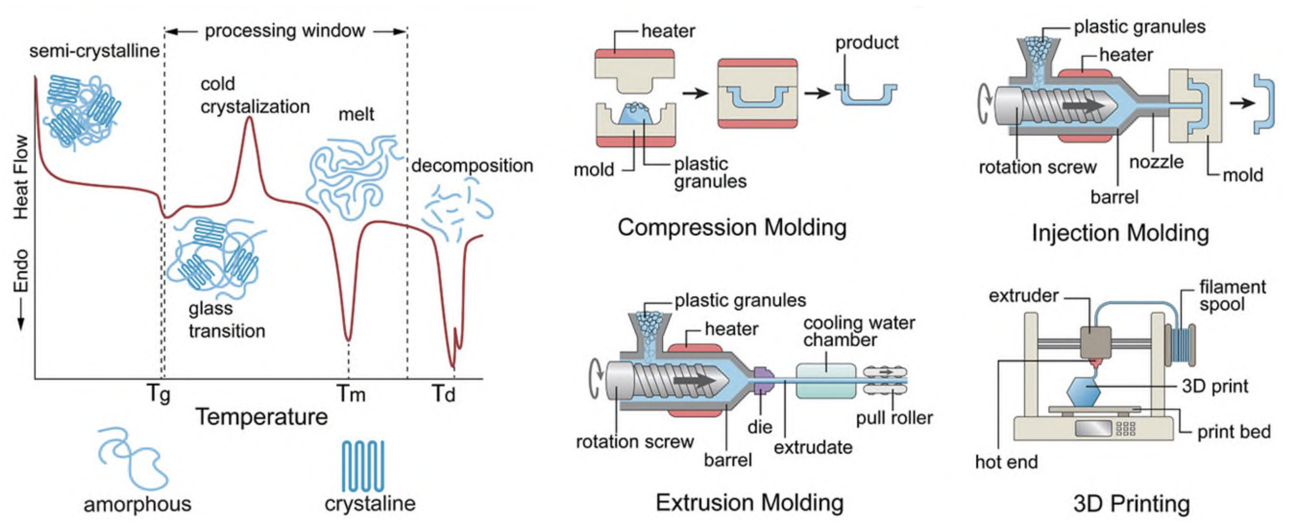
cysteine-rich (disulfide bonds)

high-throughput cloning and characterization of protein polymers – *discovery, design to function*

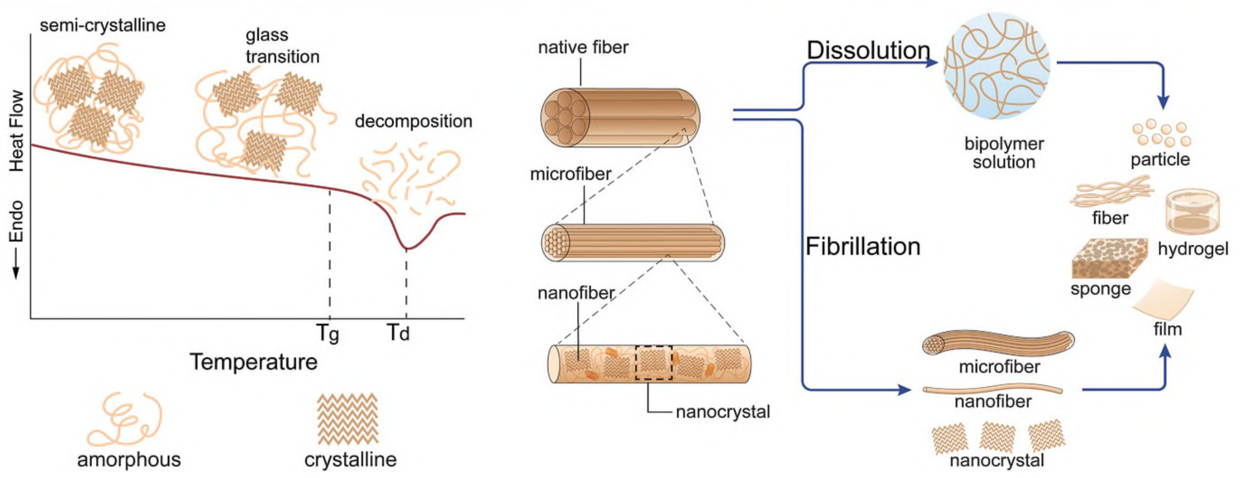


Processing - thermoplastic molding of biopolymers vs. synthetics

Synthetic polymers



Biopolymers: chitin, cellulose, silk

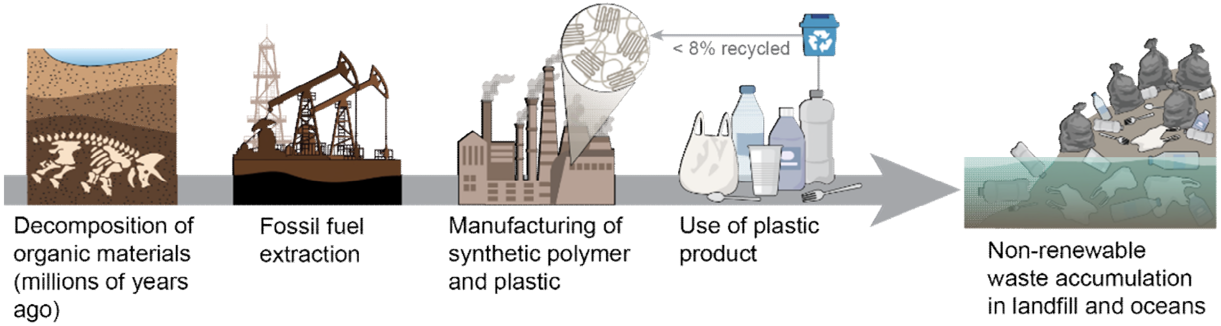


Li et al., *Advanced Materials* 2021

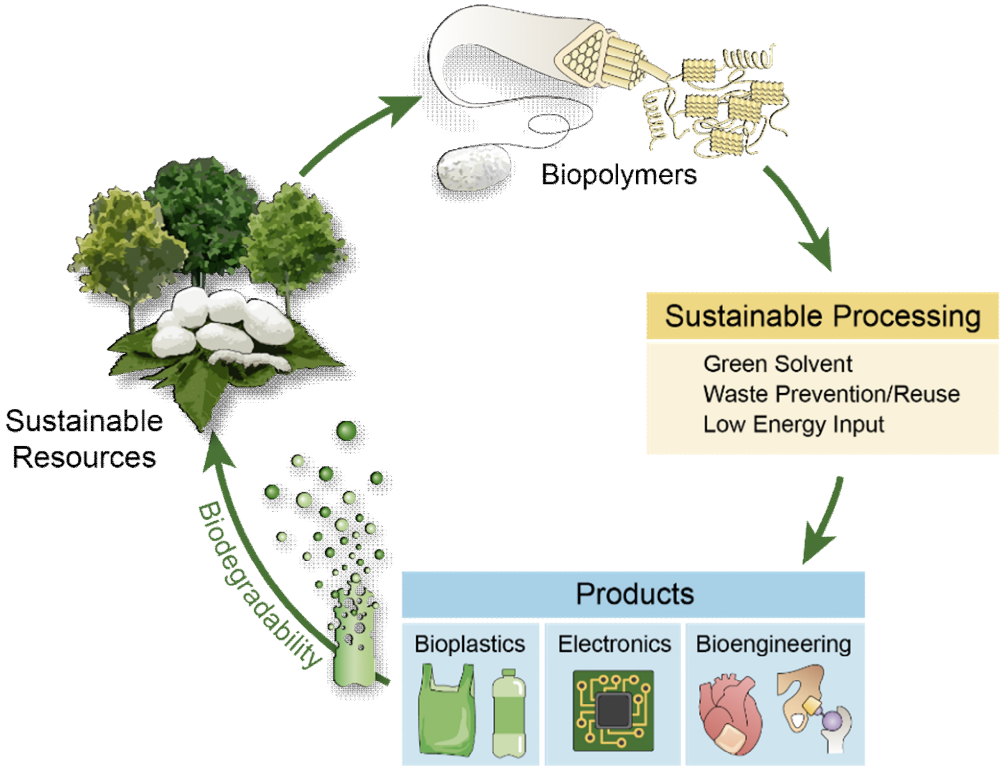
Sustainability

linear lifecycle of synthetic polymers vs. circular lifecycle of biopolymers

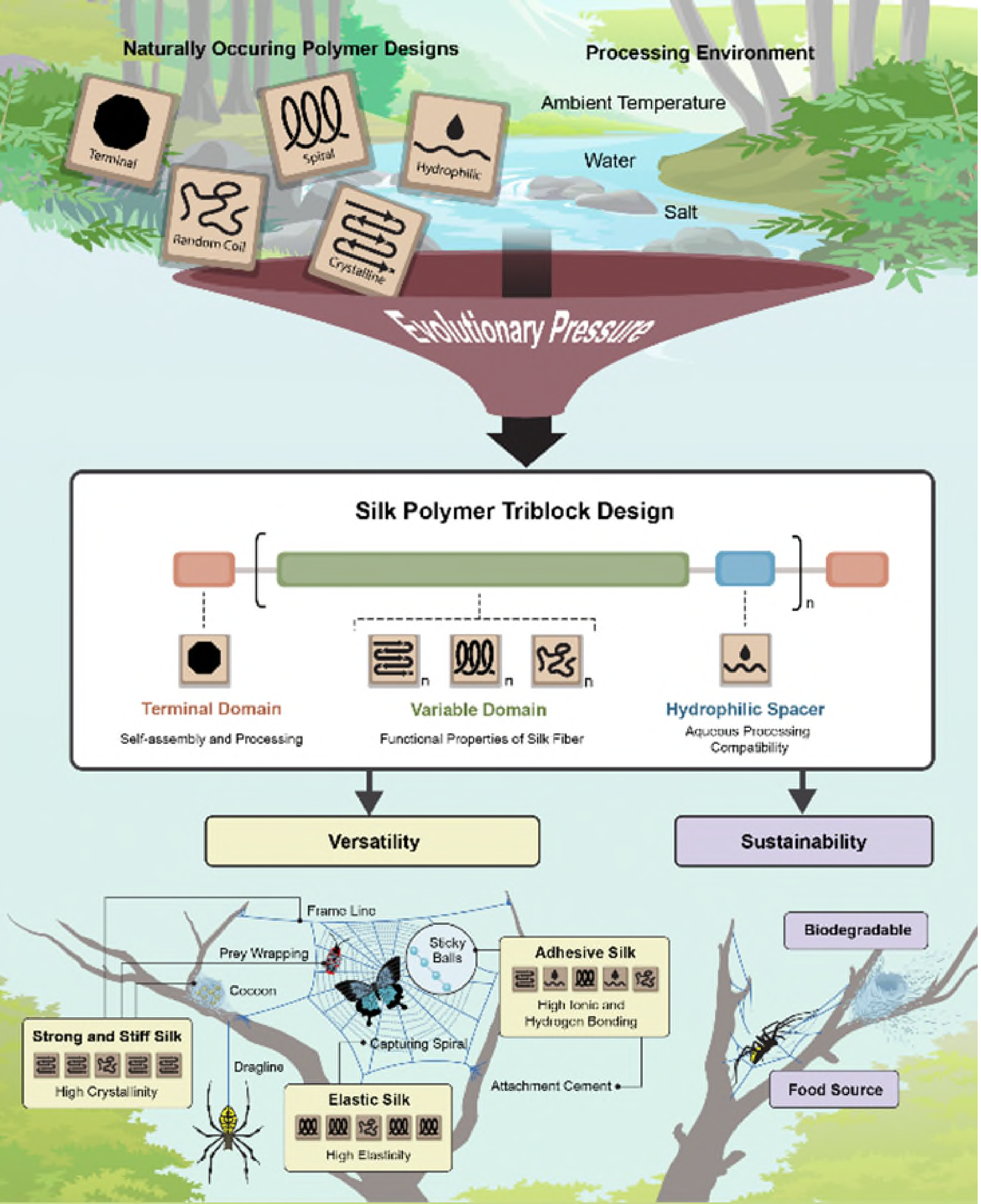
Linear – fossil fuels



Circular – silk protein



Li et al., ***Advanced Matls,*** 2021

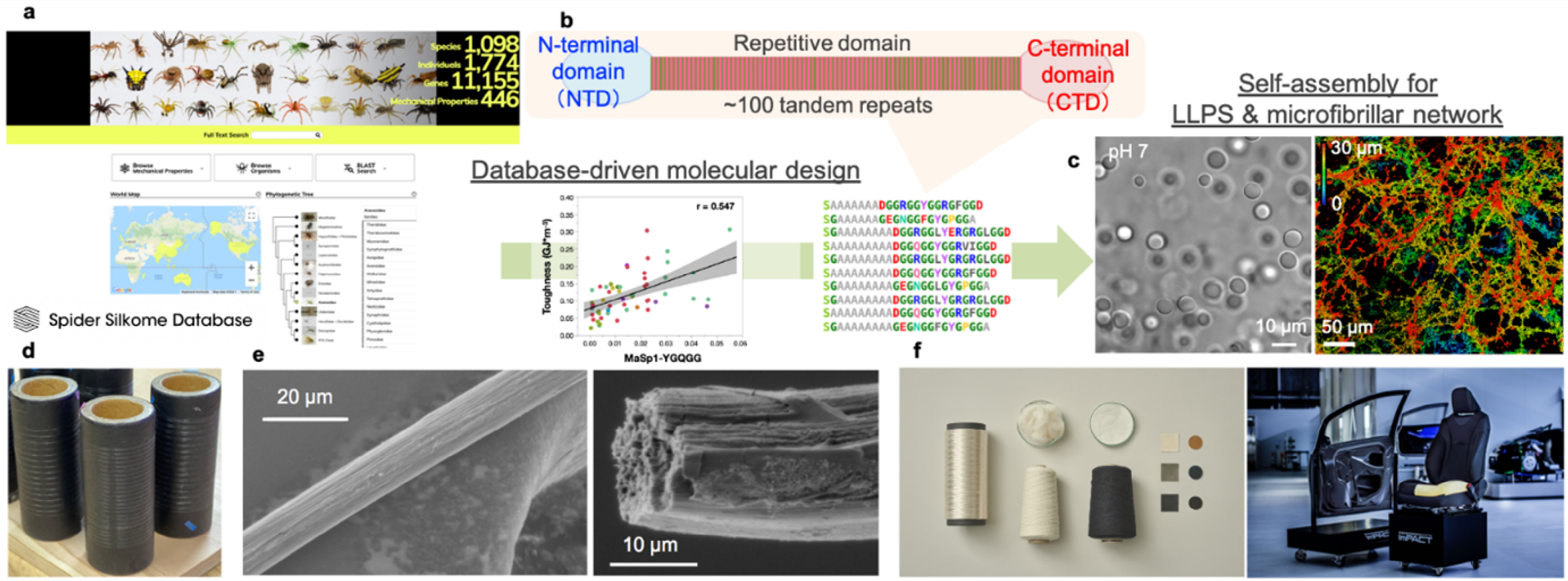


Amazing Materials (silks)

- **sustainable** production in nature
- **mimic, learn, model, utilize**

Numata and Kaplan, Adv. Matls, 2024

Silks – sustainable materials for the future



Spider silk big database-driven molecular design for inducing unique self-assembly including liquid-liquid phase separation (LLPS) and microfibrillar network formation

a)“Spider Silkome Database” (Silkome) (https://spider-silkome.org/)

b) Domain structure of the major ampullate spidroin (MaSp), mostly composed of N-terminal, C-terminal, and repetitive domains

c) Spinning mechanism of spider silk proteins from the secondary structures, liquid droplets (optical image), microfibrillar networks (confocal laser scanning microscopy image) to spider dragline

d) Artificial spider silk fibers produced through LLPS process without organic solvent

e) SEM images of artificial spider fibers produced via LLPS, bundle structures of microfibrils

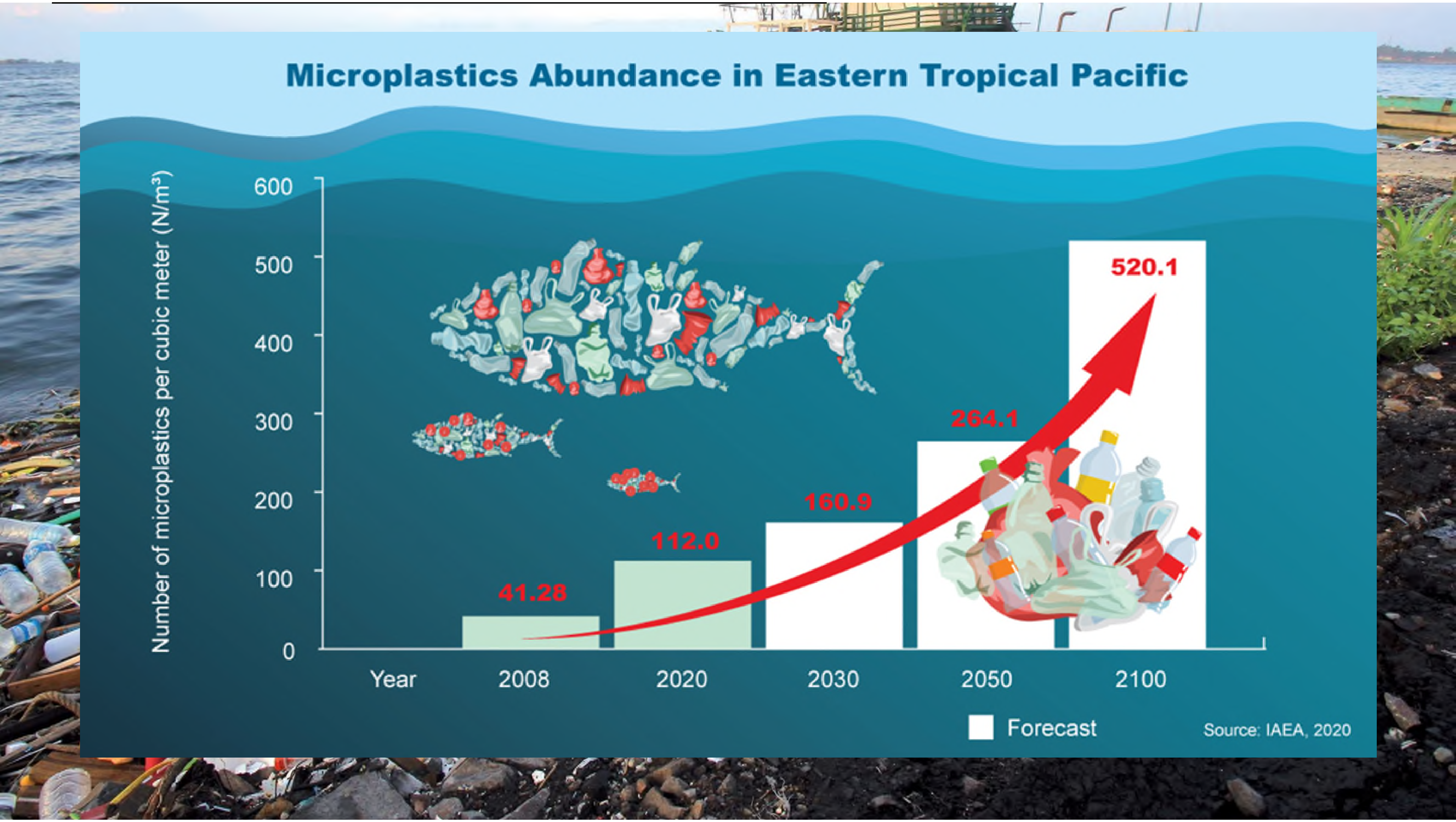
f) products generated from artificial spider silks or spider silk-like structural proteins (left) and spider silk-like structural proteins-based car doors developed in JST-ImPACT project, Japan

Numata and Kaplan, Adv. Matls, 2024

micro- and nano-plastics in marine environments

physical & chemical impact on wildlife: chemical carriers, nondegradable, accumulation…..

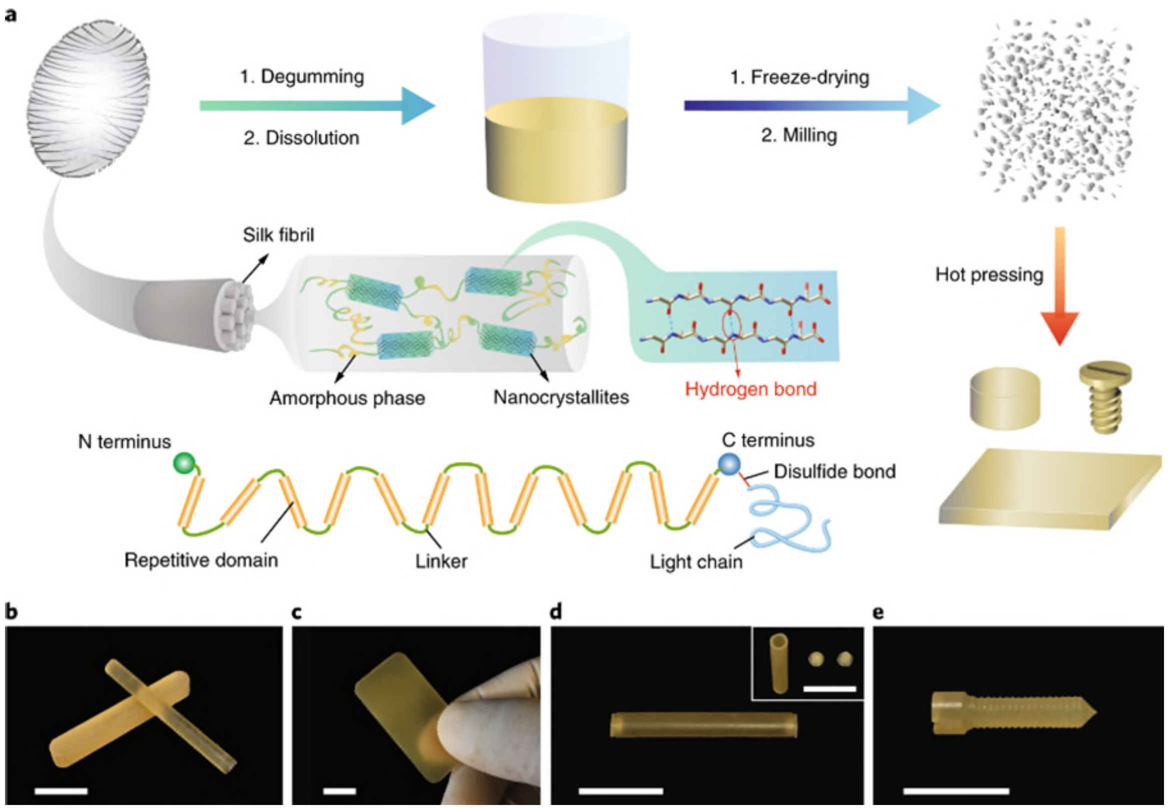
micro- and nano-plastics in marine environments



Source: IAEA, 2020

physical & chemical impact on wildlife: chemical carriers, nondegradable, accumulation…..

Thermoplastic Silk Plastics – sustainable option



- heat
- pressure

- Silk fibroin is extracted from silk cocoons and freeze-dried into powder
- Silk powder is hot-pressed in a metallic mold to prepare plastics

Source: https://www.nature.com/articles/s41563-019-0560-8

Engineered living materials enable next-generation exponential manufacturing due to their regenerative capabilities

Heveran et al., (2020). Biomineralization and successive regeneration of engineered living building materials. *Matter*

Printing Underwater – *functionalized (living) architectures*

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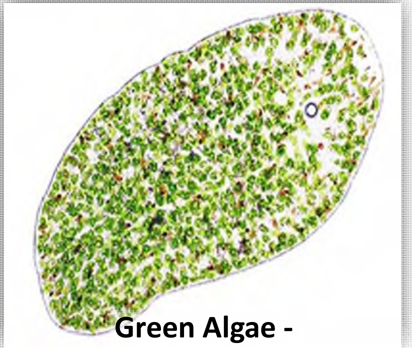
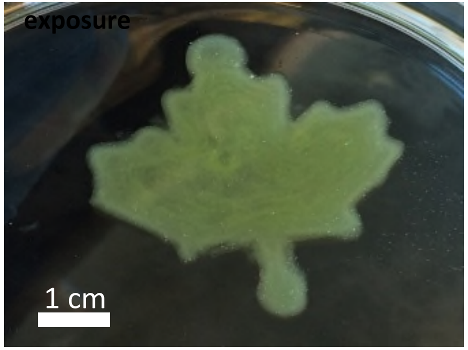


Green Algae - Functionality

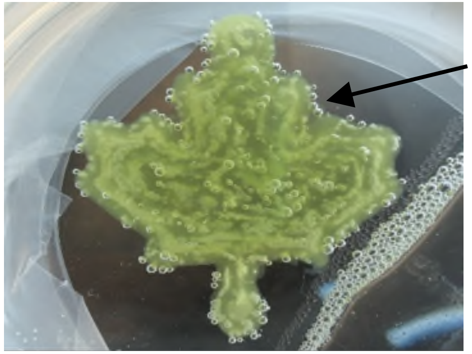
=

Living cell-enabled functional architectures (photosynthesis):

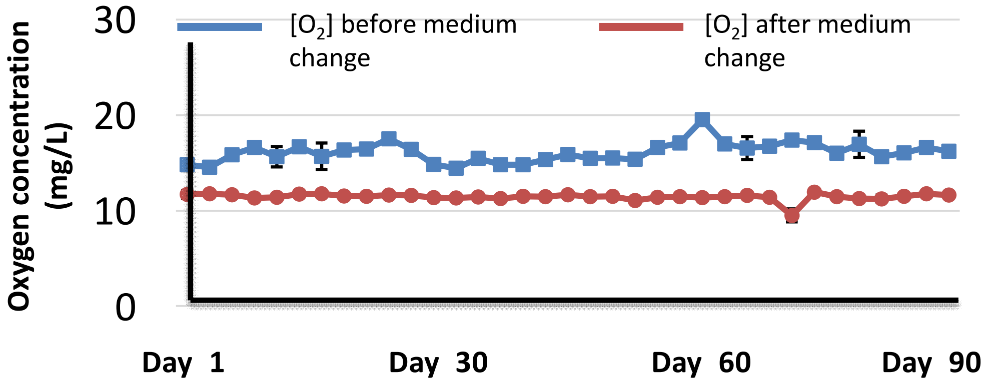
Algae/silk gel – before light exposure



Algae/silk gel – after light exposure



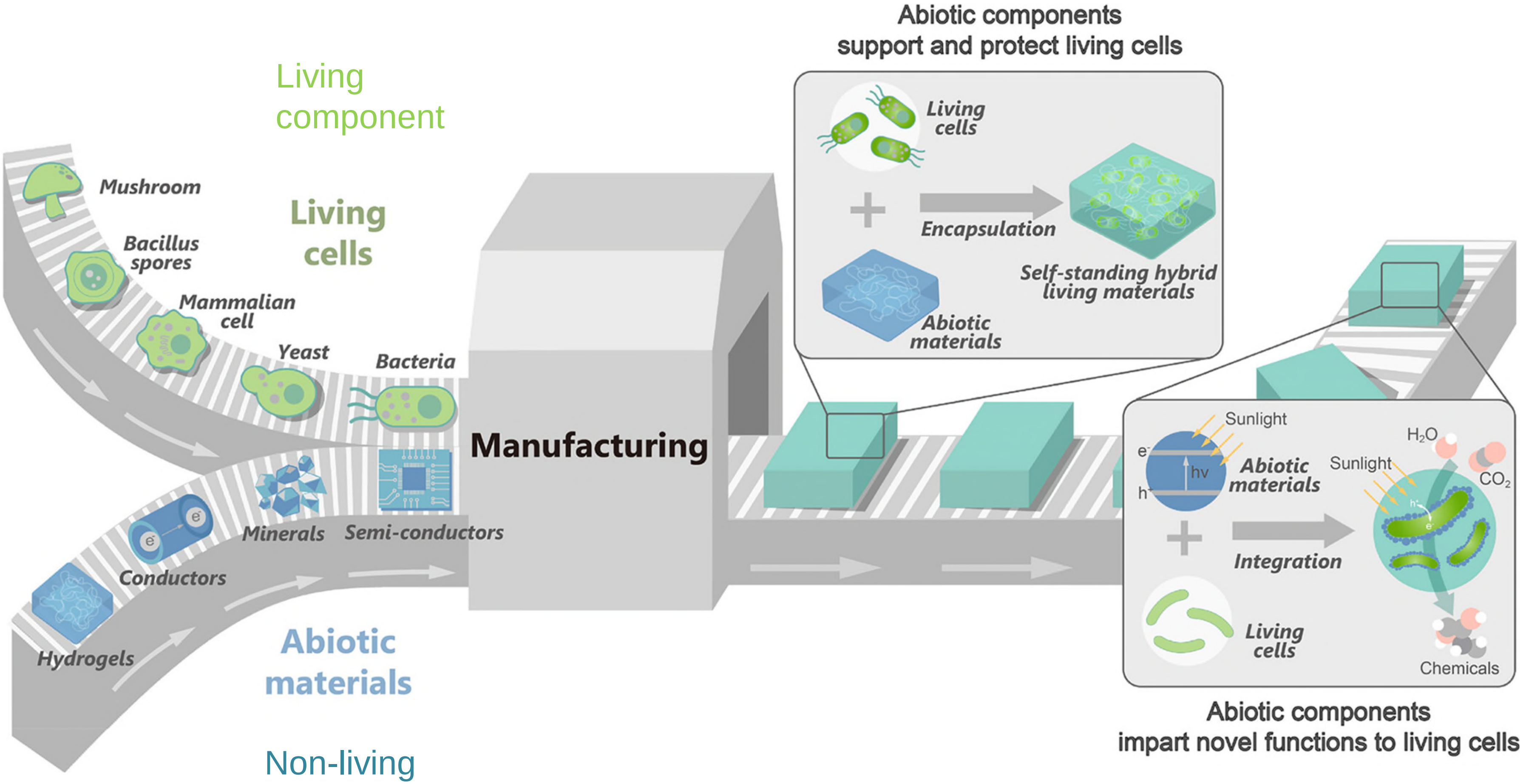
Oxygen production stable for >3 months



Algae in hydrogels (3D printing) – oxygen generation over extended time frames

manufacturing of the living material determines which functionalities are conferred

Living component



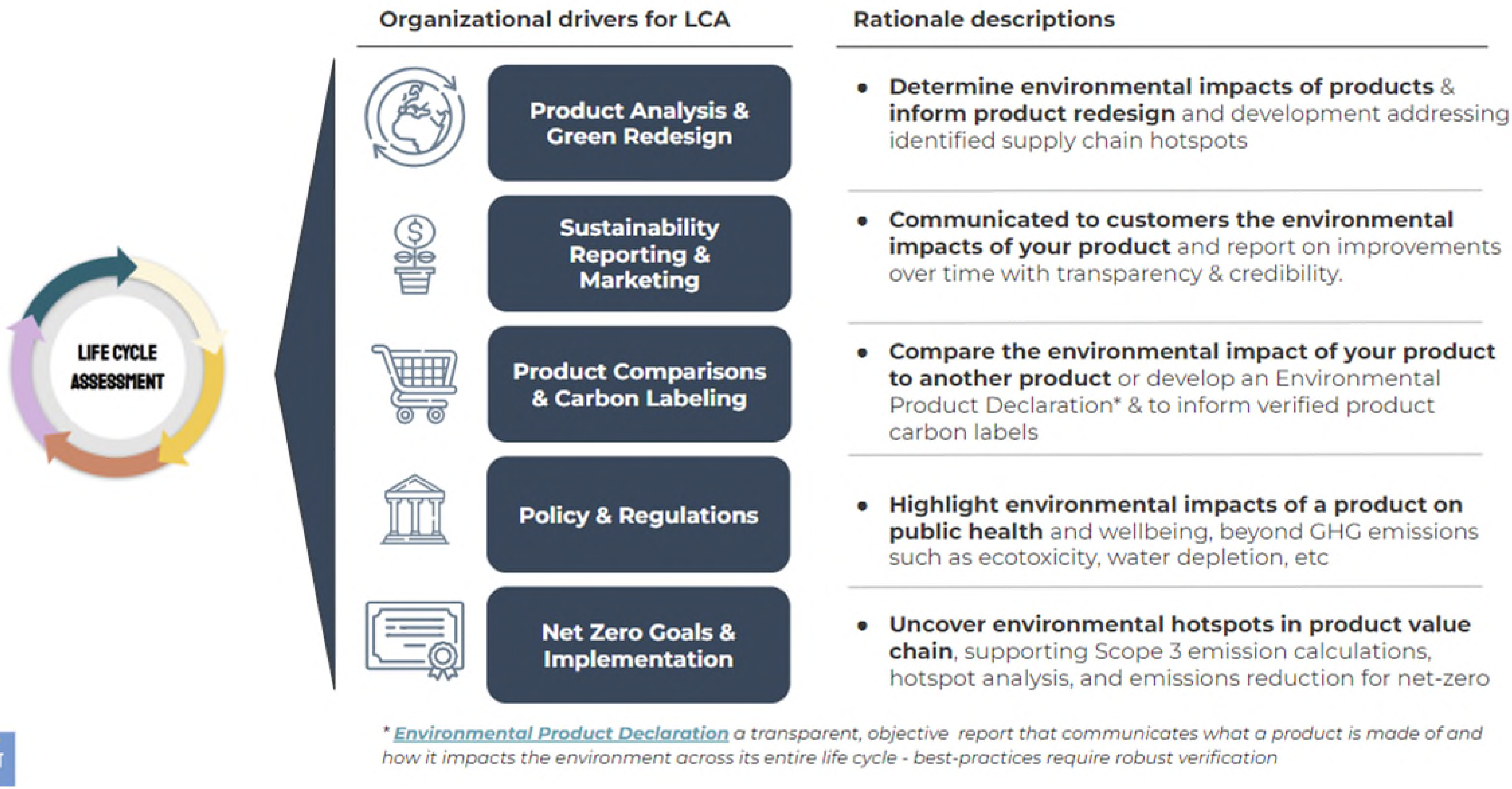
Non-living component

Wang et al. (2022). Engineered living materials for sustainability. *Chemical Reviews*

Challenges to utilizing sustainable materials

- Limited availability
- Cost considerations
- Certification and standards
- Quality and performance
- Education and awareness
- Regulatory compliance
- Supply chain transparency
- Waste management
- Local sourcing

Lifecycle analysis (LCA)



Organizational drivers for LCA	Rationale descriptions
Product Analysis & Green Redesign	**Determine environmental impacts of products** & **inform product redesign** and development addressing identified supply chain hotspots
Sustainability Reporting & Marketing	**Communicated to customers the environmental impacts of your product** and report on improvements over time with transparency & credibility.
Product Comparisons & Carbon Labeling	**Compare the environmental impact of your product to another product** or develop an Environmental Product Declaration* & to inform verified product carbon labels
Policy & Regulations	**Highlight environmental impacts of a product on public health** and wellbeing, beyond GHG emissions such as ecotoxicity, water depletion, etc
Net Zero Goals & Implementation	**Uncover environmental hotspots in product value chain**, supporting Scope 3 emission calculations, hotspot analysis, and emissions reduction for net-zero

** Environmental Product Declaration a transparent, objective report that communicates what a product is made of and how it impacts the environment across its entire life cycle - best-practices require robust verification*

The Future:

Sustainable materials as materials

Sustainable materials for food

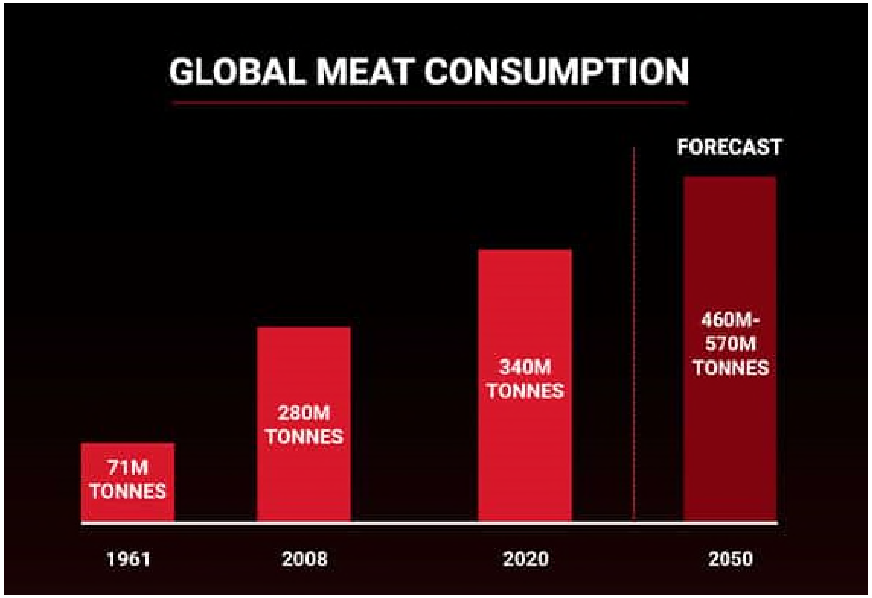
Modeling and simulation

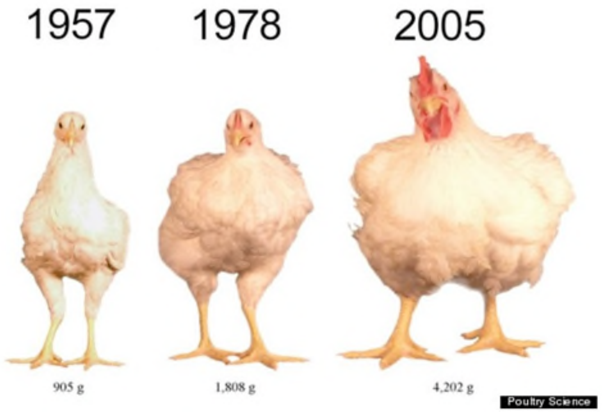
Synthetic biology

Reminders for inspiration

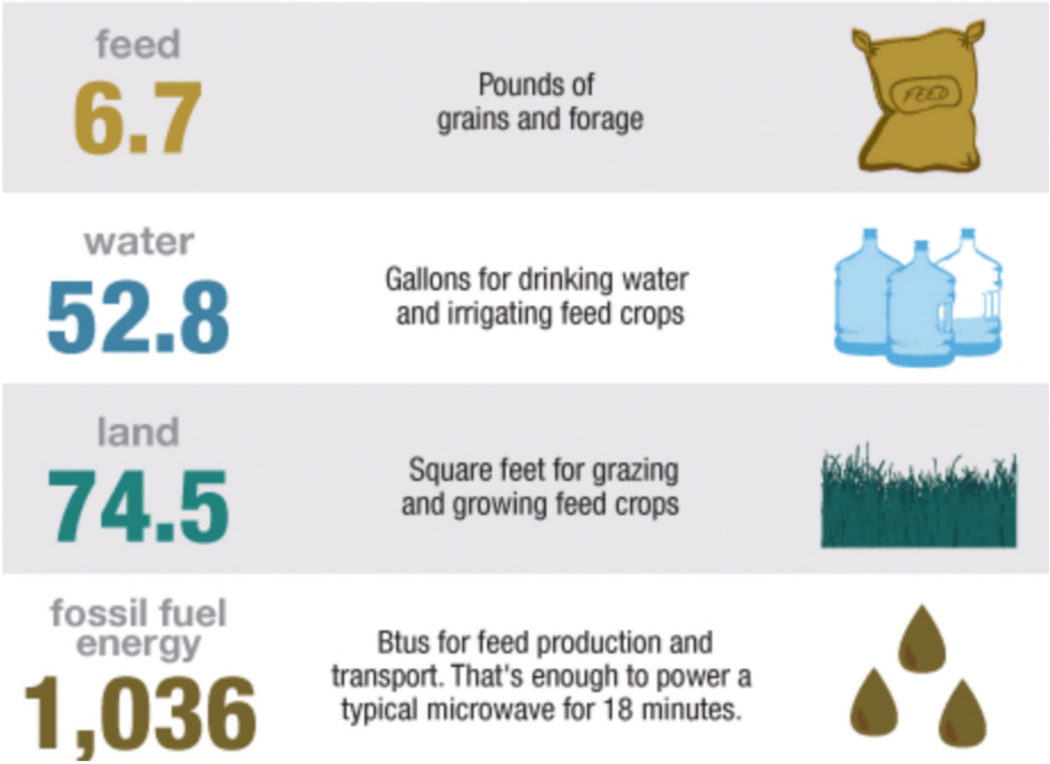
The Growing Demand for Meat:

- Applicable worldwide
- Increasing economic status = increase in meat consumption
- Consumer campaigns have failed to reduce growth





A model of inefficiency:



feed	6.7	Pounds of grains and forage
water	52.8	Gallons for drinking water and irrigating feed crops
land	74.5	Square feet for grazing and growing feed crops
fossil fuel energy	1,036	Btus for feed production and transport. That's enough to power a typical microwave for 18 minutes.

resources required to produce a *quarter-pound of beef*

Capper, J. Animal Science, 2011

The alternative protein landscape is divided into three main pillars

Plant-based

Photo courtesy of Beyond Meat

Fermentation

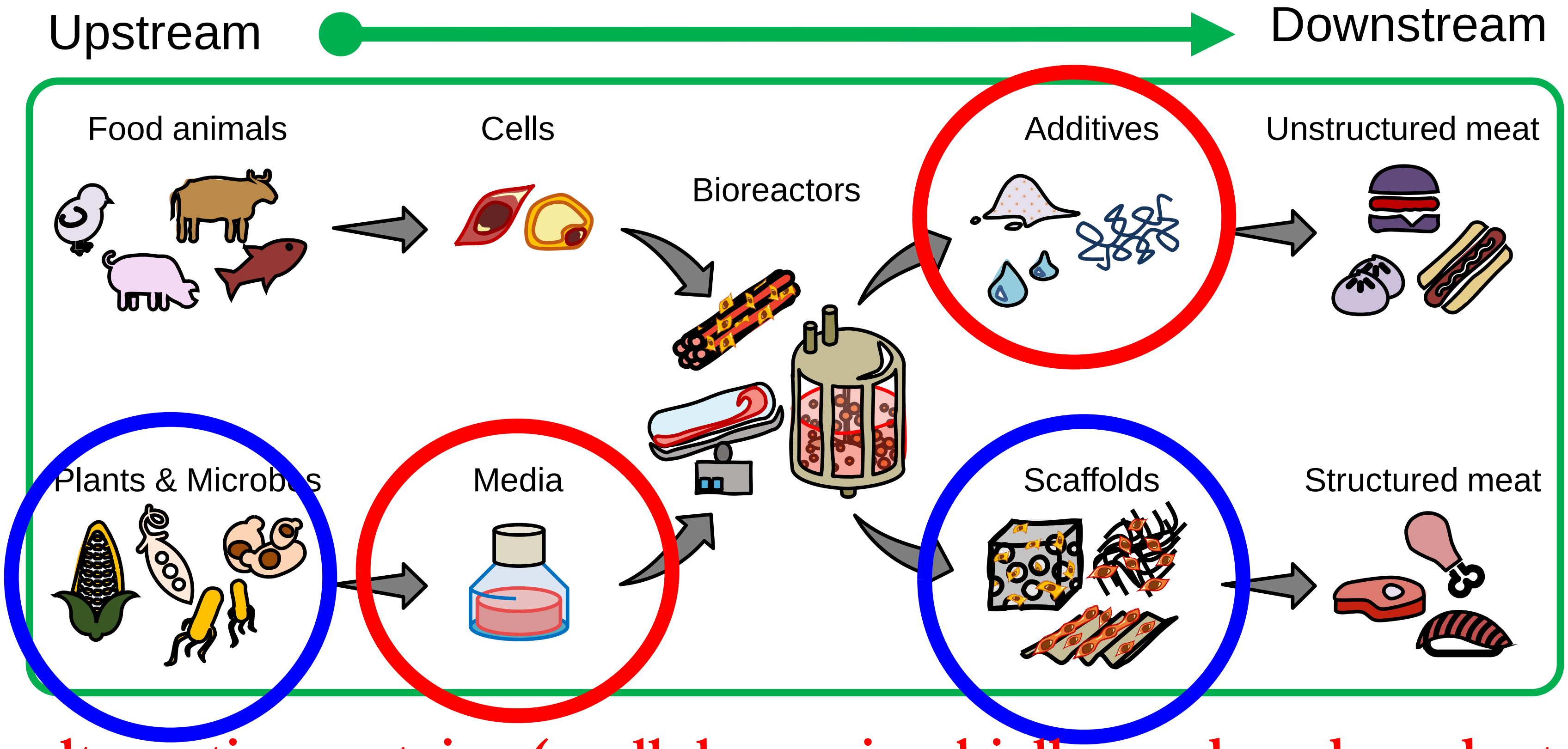
Photo courtesy of Ecovative Design: Atlast Food Co.

Cultivated

Photo courtesy of Memphis Meats

Future Foods - Cellular Agriculture

Integrated plants, alternative proteins & cellular production - process



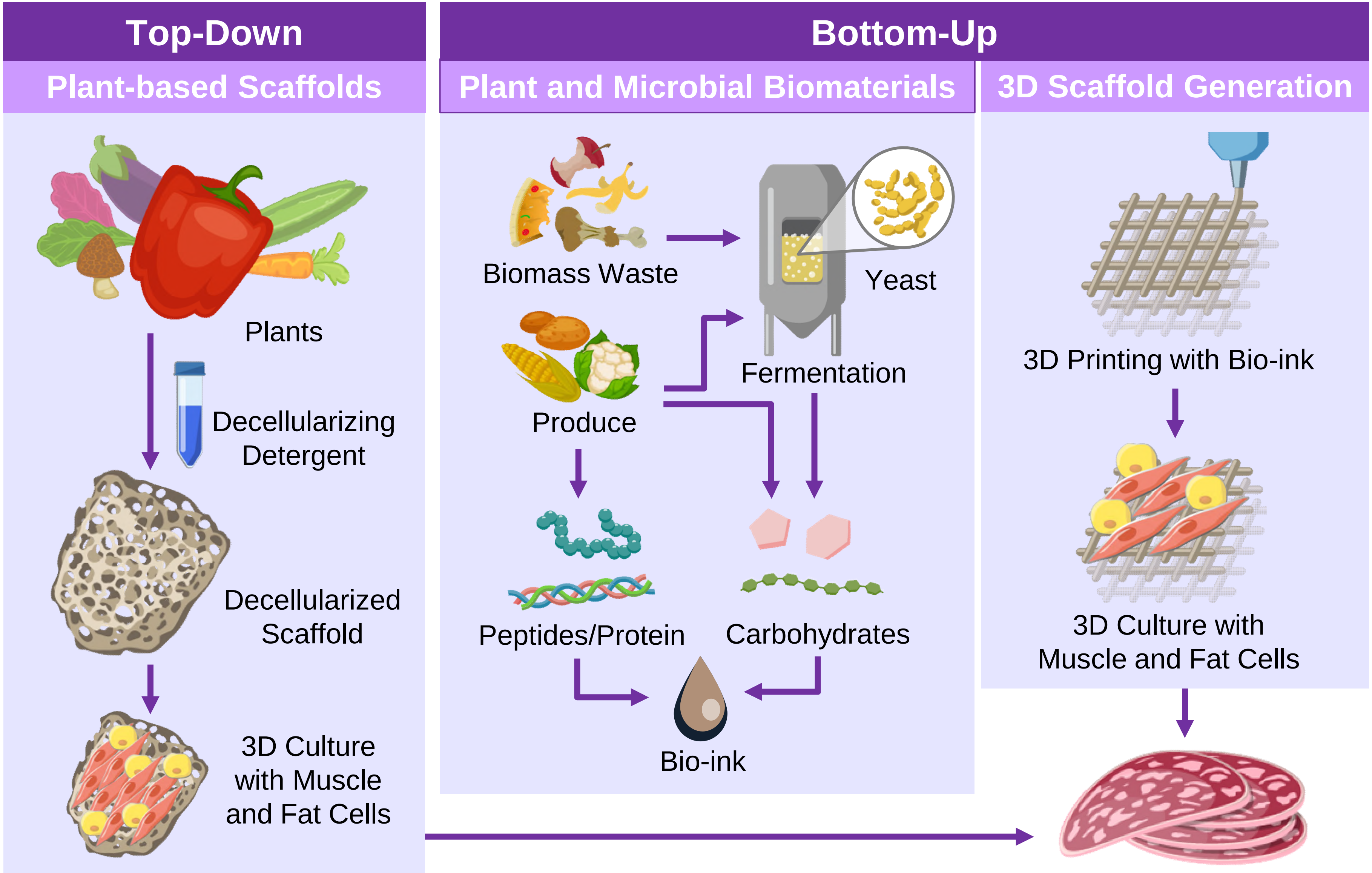
alternative proteins (acellular - microbially produced products)

plant-derived materials (acellular - plant products)

cellular agriculture - tissue engineering (cells as key ingredients)

Sustainable Materials - Foods

Sustainable, Food-Safe, Edible Biomaterial Scaffolds



Top-Down

Plant-based Scaffolds

Plants

Decellularizing Detergent

Decellularized Scaffold

3D Culture with Muscle and Fat Cells

Bottom-Up

Plant and Microbial Biomaterials

Biomass Waste

Yeast

Fermentation

Produce

Peptides/Protein

Carbohydrates

Bio-ink

3D Scaffold Generation

3D Printing with Bio-ink

3D Culture with Muscle and Fat Cells

Questions of Scale

biopharmaceuticals [protein biologics, gene therapy, monoclonal antibodies]

→ bioreactors 1L to ~20,000L, average 3,500L

→ total capacity ~17 million liters → generates 1 and 30 g/L of specific biopharmaceutical, or total of **8.5 to 30 metric tons per year globally**

These production scales pale for needs with sustainable foods

→ livestock meat production worldwide 329 million metric tons yearly + 84 million metric tons of fish aquaculture → projected to grow 10-15% yearly to **476 million metric tons by 2030**.

→ If we assume ~10% comes from sustainable foods in the next 25 years = 47.6 million metric tons of food. If we assume ~10% of this mass is from cells (cellular agriculture) = ***~43 million metric tons of biomaterials required for edible scaffolds each year*** worldwide for foods

Gordon et al., in review, Nature Matls. Rev, 2024

Questions of Scale

current production levels of the most common biopolymers

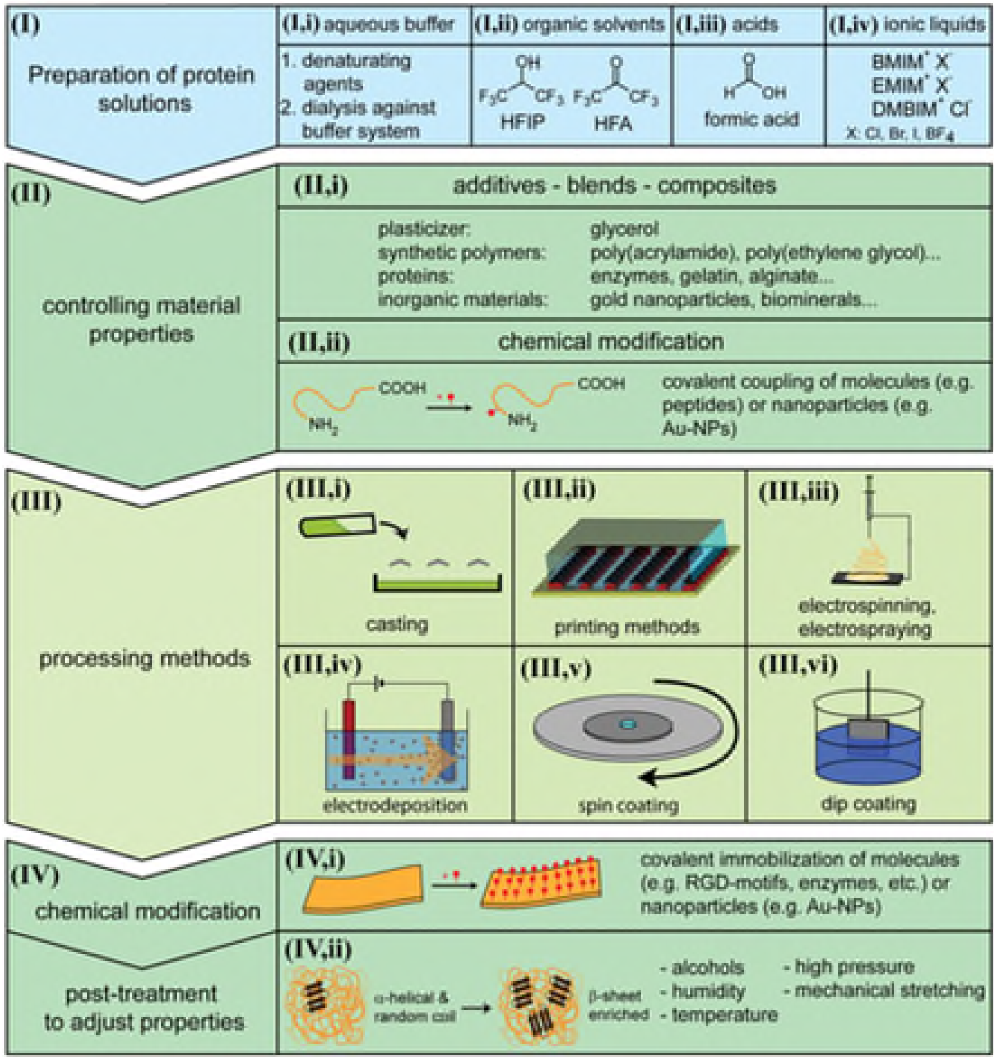
Material	Estimated Annual Production (metric tons)	Reference
Polysaccharides		
Cellulose (plant, bacterial)	75,005,000,000	145–147
Starch (amylose, amylopectin)	98,000,000	148
Chitin & Chitosan	8,000,100,000	149–151
Sodium Alginate	23,000	152
Konjac Glucomannan	Unknown	
Pectin	60,000	153
Agar	12,500	154
Carrageenan	67,000	155
Xanthan Gum	133,000	156
Guar Gum	522,000	157
Proteins		
Soy Protein Isolate	4,200,000	158
Pea Protein Isolate	200,000	159
Glutenin & Vital Wheat Gluten	1,200,000	160
Zein & Corn Gluten Meal	2,940,500	1,161,162

Gordon et al., in review, Nature Matls. Rev, 2024

Sustainable Materials may be Engineered to Impart Favorable Material Properties

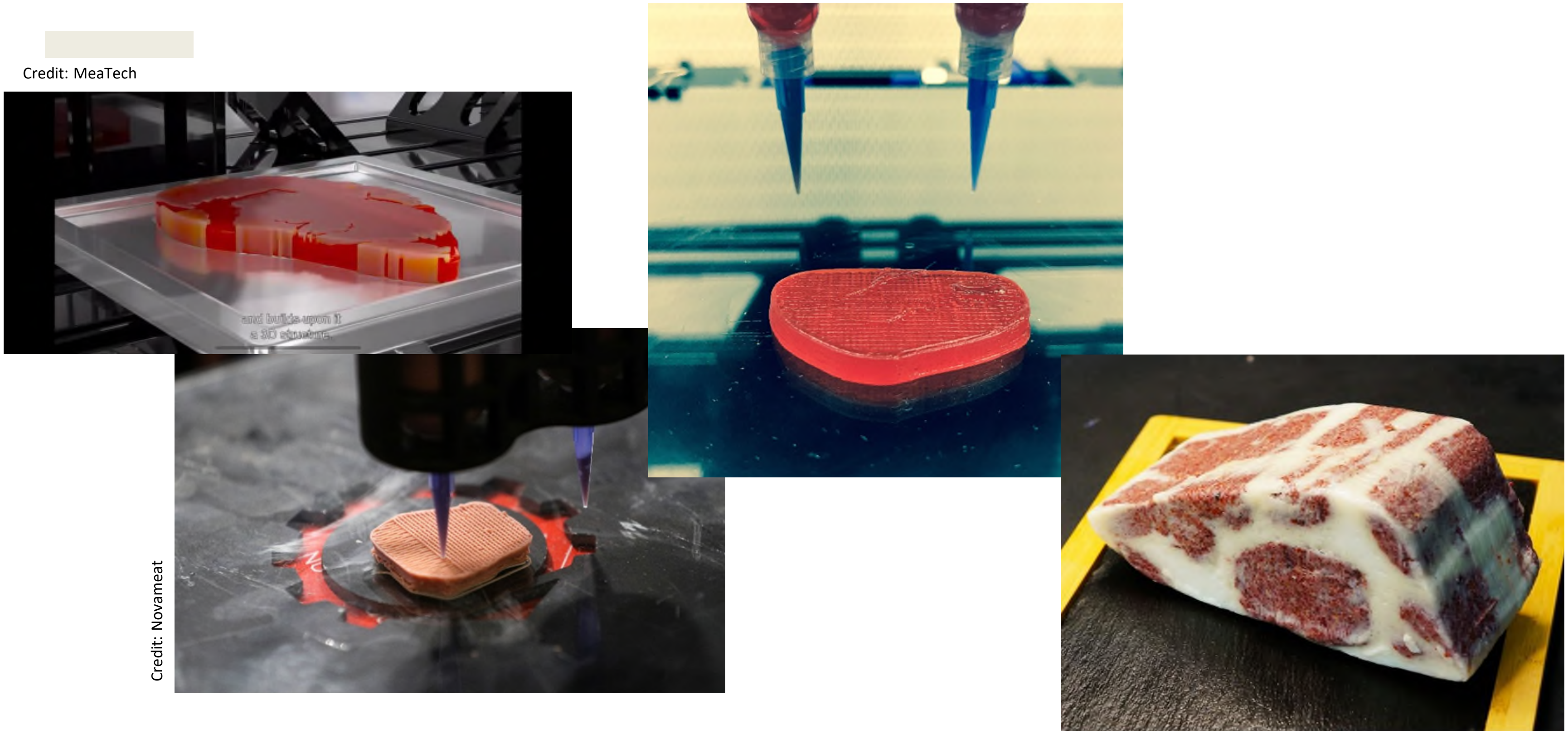
- Physical or chemical modifications, use of bio-based additives, novel processing and fabrication methods to achieve desired properties

- **Ideal Strategies –**
    - Fossil-fuel free/ reduced
    - Energy efficient
    - Biodegradable
    - Biocompatible
    - Non-toxic
    - Sterile/ sterilizable



Source: https://onlinelibrary.wiley.com/doi/full/10.1002/adsu.202000167

State of the art in 3D Printing of meat



Credit: MeaTech

Credit: Novameat

Credit: Novameat

Credit: Cocuus

<u>Challenges with Advanced Biomanufacturing:</u>

- scaling, scaling, scaling, scaling…….
- cost, cost, cost, cost…..

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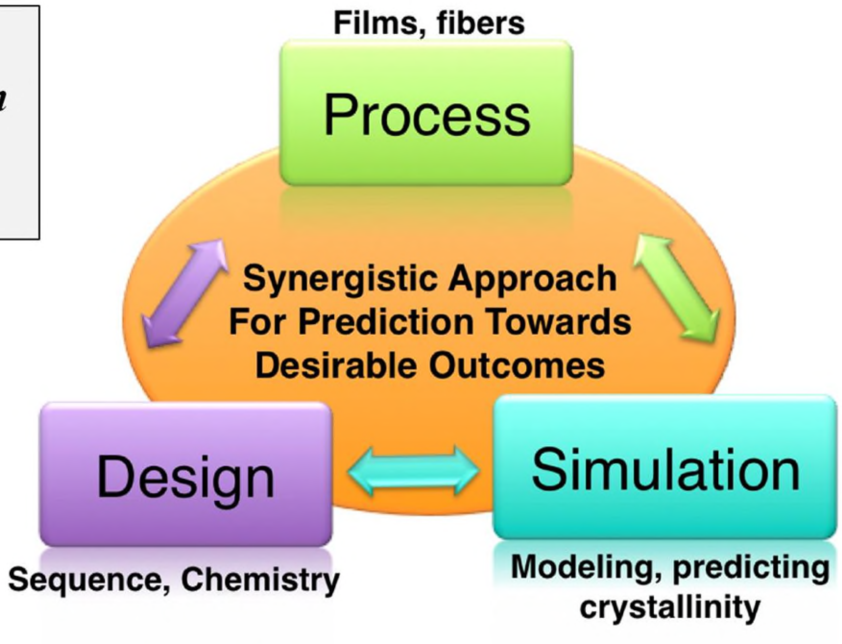
Challenge – expanded set of modeling tools to empower biopolymer discovery/applications

Models to Predict Protein Biomaterial Performance



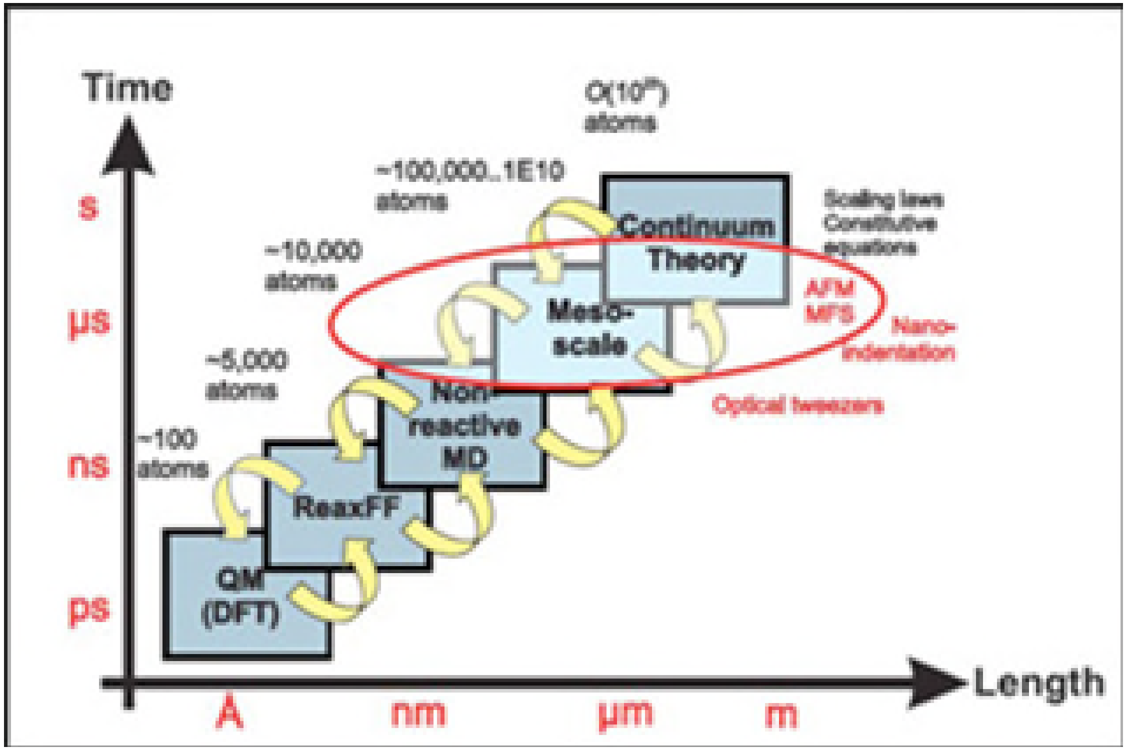
GOAL: **predictive assessments** of for protein biomaterials

→ **Reduce trial-and-error approach** with a **more rational approach**

→ **bottom-up multiscale modeling** to guide preparation of materials

Needs: high MW polymer systems
dense biopolymer matrices
other components (plasticizers, metals, second polymers…)

Modeling & Simulation – just beginning



<u>Many needs:</u>

- Computational power
- Polymer density
- Water and other plasticizers
- Additives (e.g., metals, fillers, cells….)

Artificial Intelligence & Machine Learning

Artificial Intelligence (AI) - computer systems that mimic human intelligence (simulating human thinking)
learning from data and making decisions

Machine Learning (ML) - subset of AI, achieve thinking via data analysis
algorithms that allow computers to improve performance on a task by learning from data without explicit programming
identify patterns and make predictions based on learned information

AI example: A self-driving car that uses a combination of sensors, computer vision, and decision-making algorithms to navigate a road

Machine learning example: algorithm within the self-driving car that learns to identify pedestrians and traffic signs from large datasets of images

ARTIFICIAL INTELLIGENCE FLOWCHART

Great Idea
Lorem ipsum dolor sit amet, conse ctetur adip iscing elite.

Research
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Development
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Presentation
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Artificial Brain
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Prototype
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Test
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Turing test
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Future
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Robotics
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Artificial Intelligence
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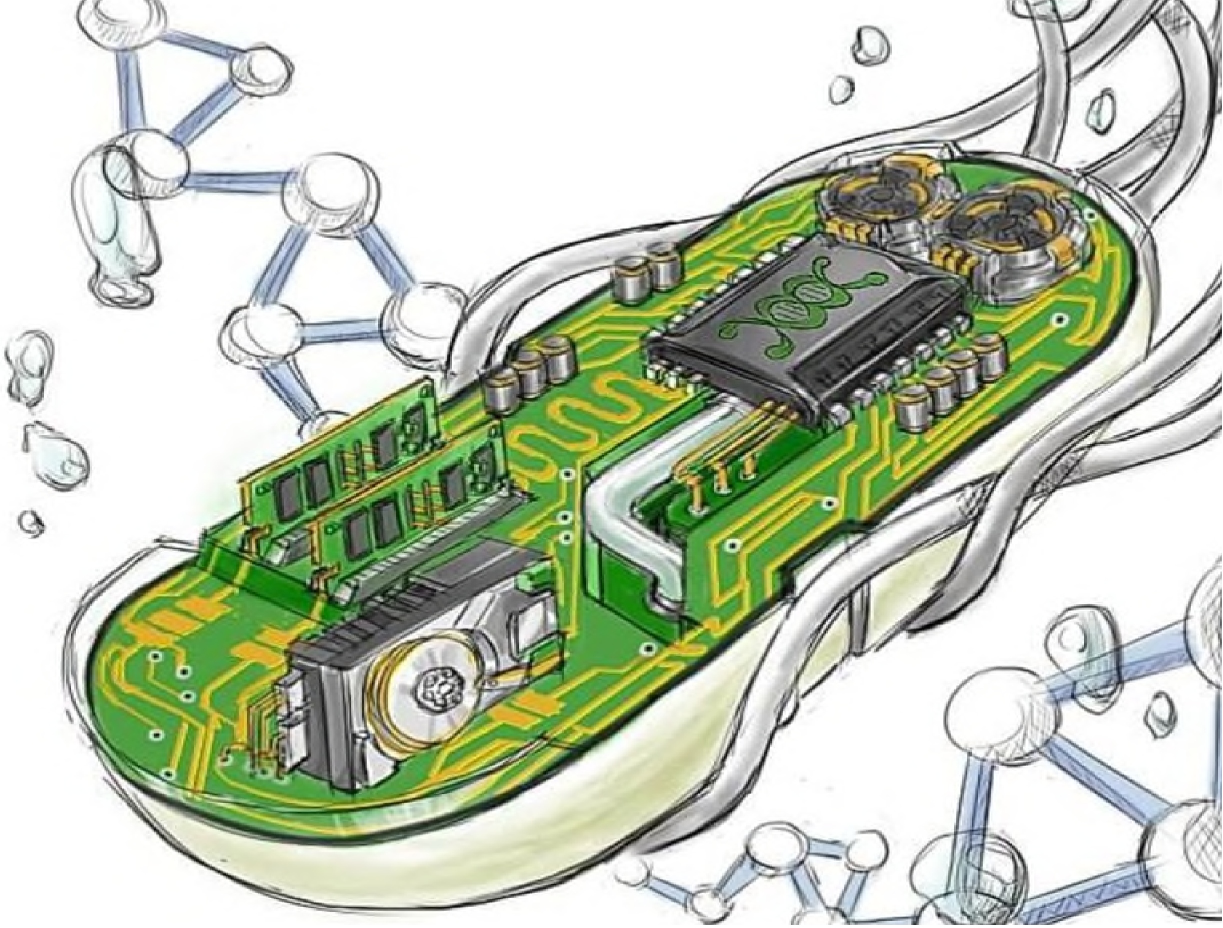
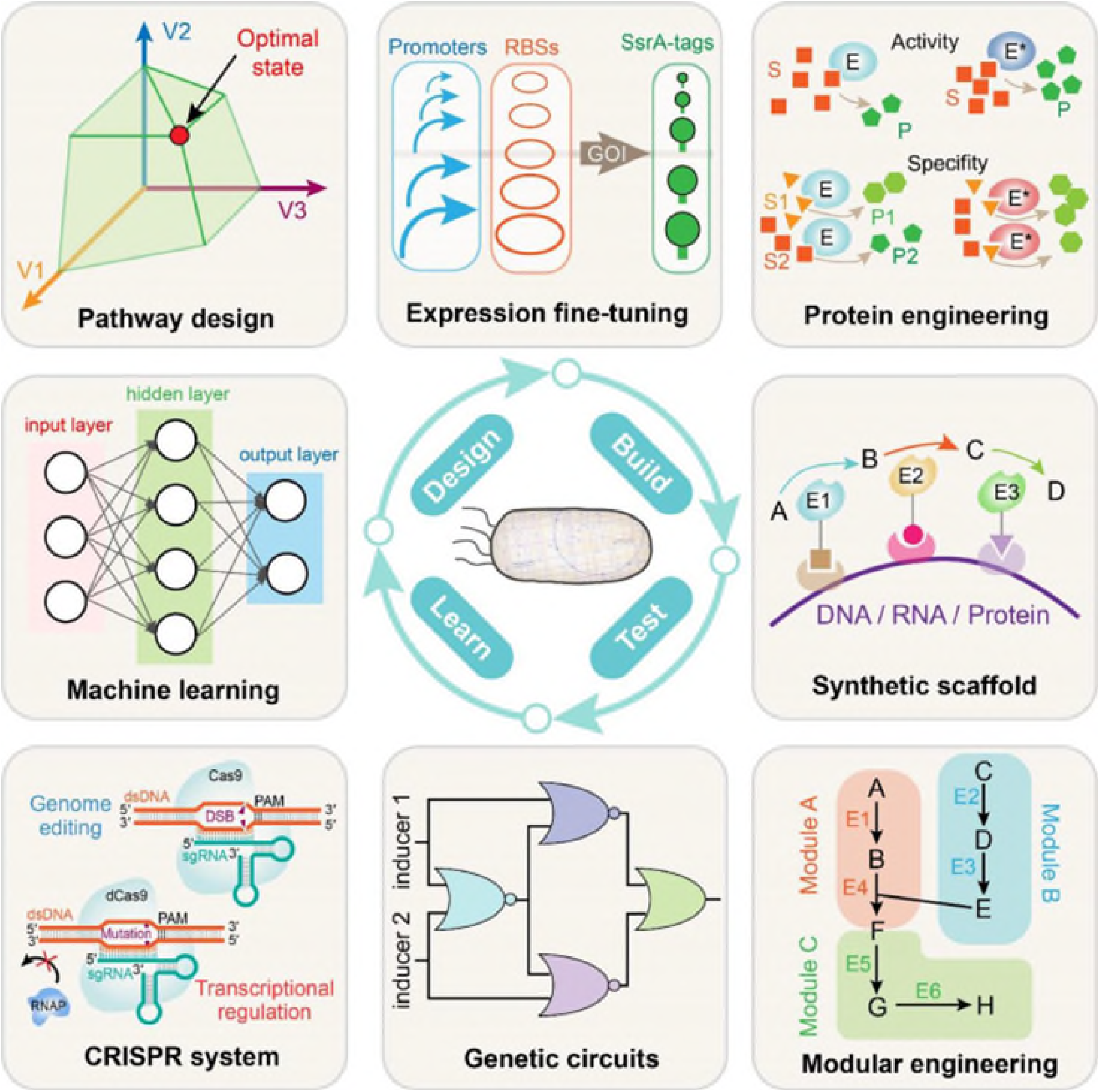
The Power of Synthetic Biology



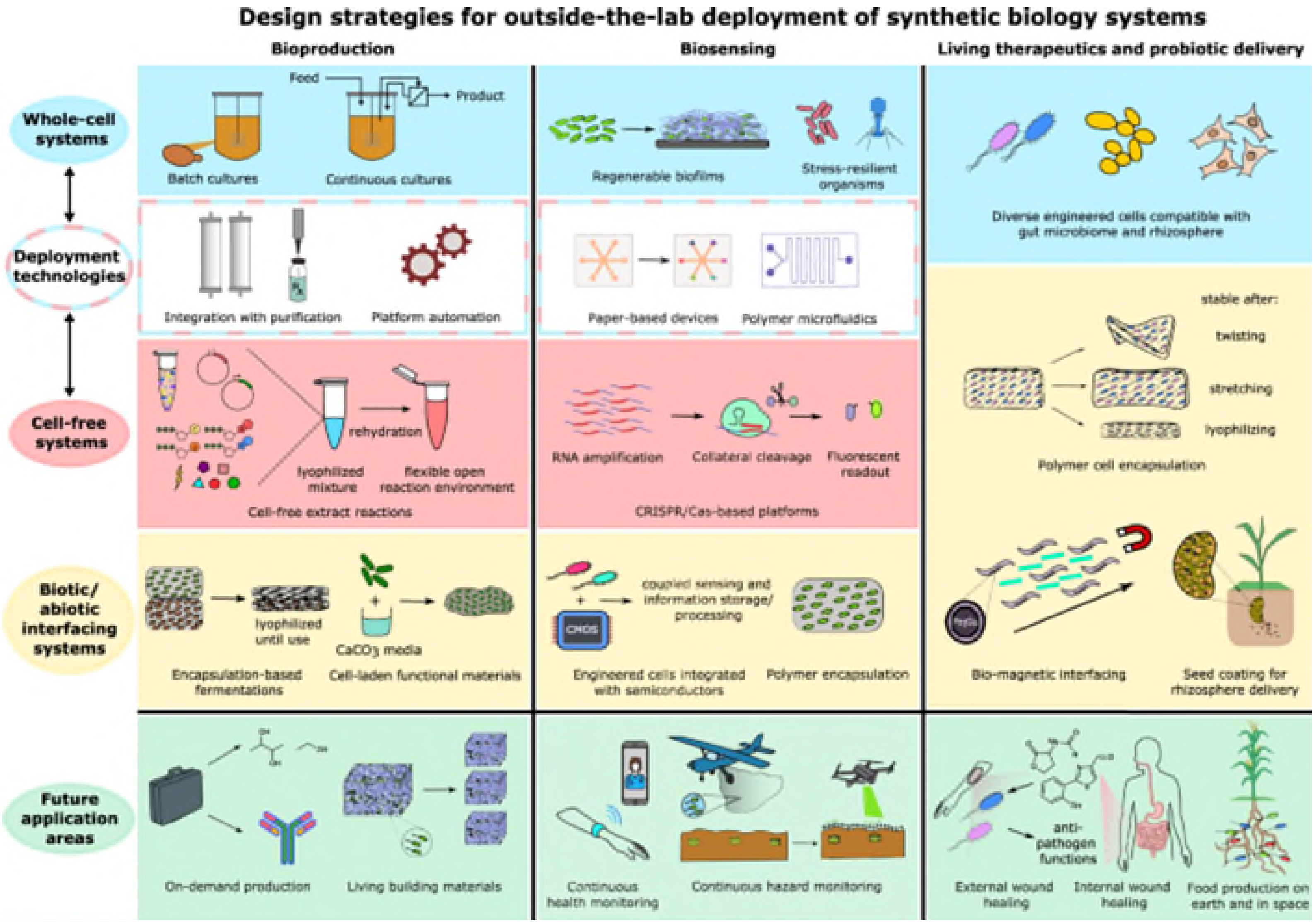
Opportunities:

- Photosynthesis – energy source
- Metabolomics – process optimization, reduced costs
- Designs for downstream processing
- Final products via programmed assembly

Power of Synthetic Biology - tools



Power of Synthetic Biology - tools


Design strategies for outside-the-lab deployment of synthetic biology systems

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First …the life of a tree

Sustainable Materials
→ trees as inspiration

simple building blocks → remarkable structures & functions
[cellulose, hemicellulose, lignin]

Structure

- Structural hierarchy – mechanics
  porous to dense (balsa to ironwood), soft to hard…
- Vascular networks, transport

Sustainable Materials → trees as inspiration

Functions

- Carbon Fixation/Sequestration, biomass production
- Enzymatic Processes – protection from infections, metabolism…
- Longevity – short to long (annuals to >1,000s of years)
- Regenerative capacity – regrow limbs, turnover in soil
- Sustainability, all aqueous, ambient – nothing wasted

Sustainable Materials
→ trees as a blueprint

The need for materials, devices, tissues and foods that reflect natural systems and sustainability has finally emerged as a significant driving force in discovery and translation for many technological needs

FORAY bioscience

Cell culture for hardwoods

Foray Bioscience Raises $3M to Restore Forests With Plant Cell Culture Tech

Some call the rise of ***biomanufacturing*** the **Third Industrial Revolution** or the **“BioRevolution”**

(others say that the “Third Industrial Revolution” is the rise in digital technologies or renewable energy)

Biomanufacturing = Using **Bio**logical systems for **manufacturing**

Question: Why are biological systems being explored as a manufacturing platform?

Possible answers:

- Need for **renewable inputs** (e.g. sugars and amino acids instead of fossil fuels and metals)
- Need for **biodegradable outputs** (e.g. protein materials, cellulosic materials)
- **Less geographic restrictions**, as bioreactors can control manufacturing conditions
- More **tunable properties** using protein engineering, metabolic engineering
- Easier **quality control** compared to agricultural farming

Solar Plunk depiction of manufacturing facilities of the future. Credit: Albert Anis

Solutions ?

President Biden issued an Executive Order to promote biomanufacturing initiative in 2022

SEPTEMBER 12, 2022

Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy

› BRIEFING ROOM › PRESIDENTIAL ACTIONS

MARCH 22, 2023

FACT SHEET: Biden-Harris Administration Announces New Bold Goals and Priorities to Advance American Biotechnology and Biomanufacturing

› OSTP › NEWS & UPDATES › PRESS RELEASES

Key takeaways:

- The Biden Administration has set a target of producing "at least **30% of the US chemical demand** via sustainable and cost-effective **biomanufacturing pathways**" within 20 years
- The U.S. Department of Defense announced an **investment of $1.2 billion in bioindustrial domestic manufacturing** infrastructure to catalyze R&D accessibility to innovators.

Source: whitehouse.gov, EO Fact Sheet and Full EO

Today & Tomorrow ……

Get Involved !!!

- here at Tufts
- beyond Tufts
- research, write, communicate, vote
- development
- activism
- behind the scenes or in the scenes
- be active not passive