École polytechnique fédérale de Lausanne

Institute of Materials - Institute of Bioengineering

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Supramolecular NanoMaterials and Interfaces Laboratory

NaCRe: Nature Inspired Circular Recycling

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桑缪 썬밀 सानमिल ΣουNMιΛ سنمل СаНМПЛ סאנמי״ל

The Problem

Polymer-based materials are one of the best materials class that exists, as they are light, versatile, easy to process, and (so far) inexpensive. As such they are pervasive, being present in basically any technology field.

But:

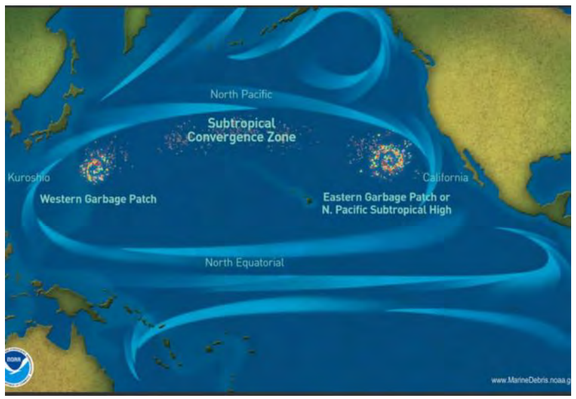
Polymers end of life is a problem, they are not meant to degrade and (due to their high entropy-content) they are intrinsically very hard to dissolve.

So:

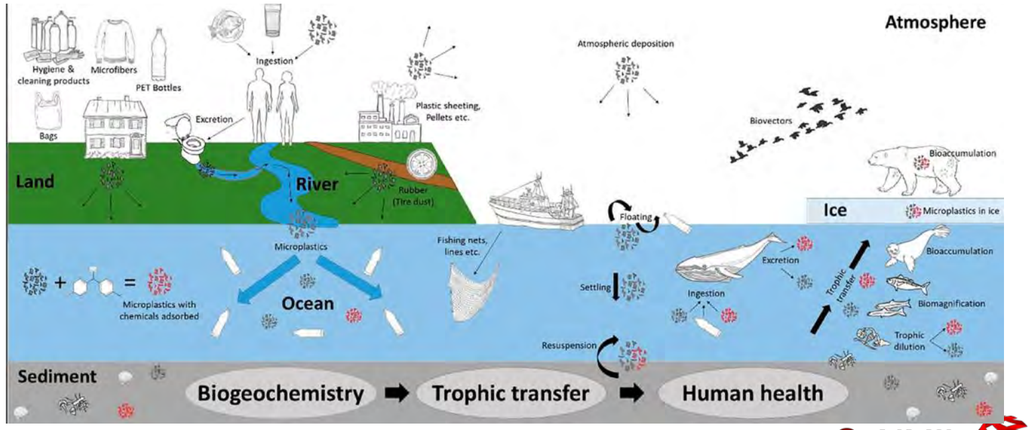
Polymer end of life is problematic, today one of three things happens to plastics at the end of their life-cycle.

They get burnt

They end up in the ocean



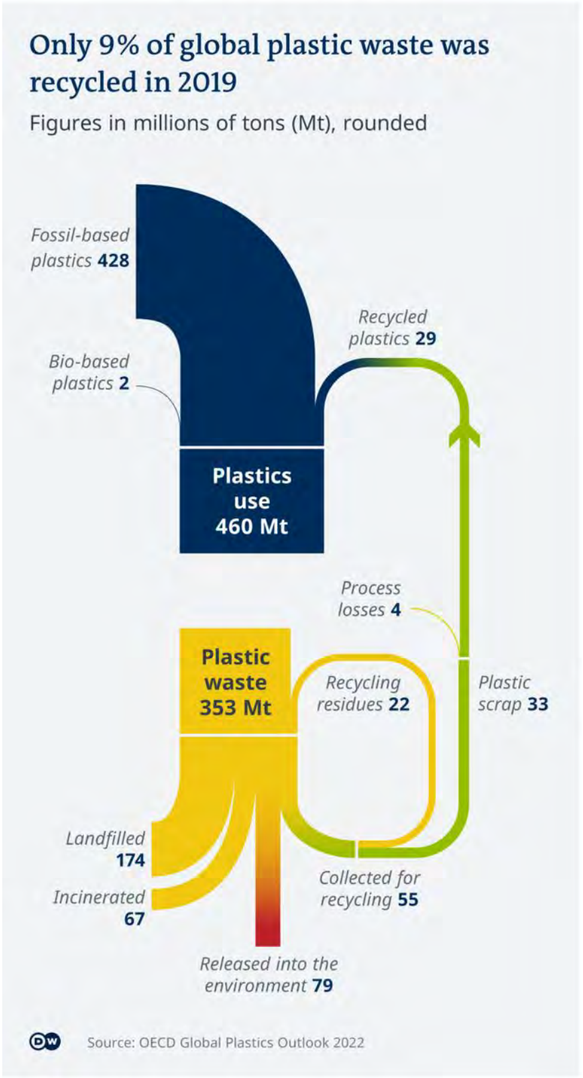
They slowly degrade in microparticles



The magnitude of the problem

An estimated microplastic generation of:
~7000 ton in the roads of Switzerland
~400000 ton in the roads of Europe

The Great Pacific Garbage Patch covers an estimated surface area of 1.6 million Km^2, an area three times the size of France



Current Solutions

75% of the plastic we produce, in theory, is recyclable but:

- **virgin plastic is too cheap**
- **recycling with most of the current approaches implies a loss of materials' performance**
- **there are entire countries that have no infrastructure for recycling**

<u>There are other proposed solutions:</u>

- **Upcycling**
- **Depolymerisation to monomers**
- **Biosourced/biodegradable polymers**

<u>But they all suffer for</u>

- **Intrinsic limitations**
- **Infrastructure needs**
- **Lack of "recycle by design" culture**

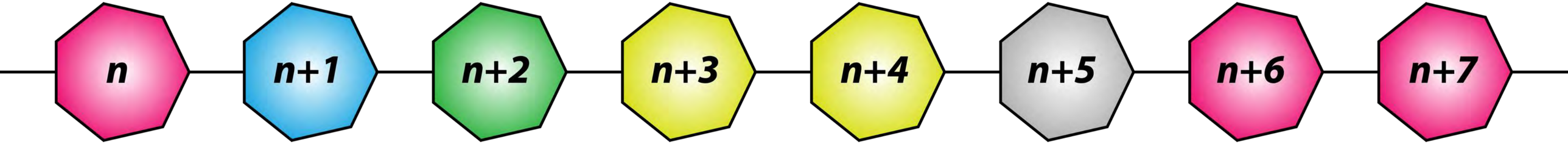
Natural Polymers

Arguably Nature's most abundant materials are polymers: polysaccharides, proteins, and nucleic acids

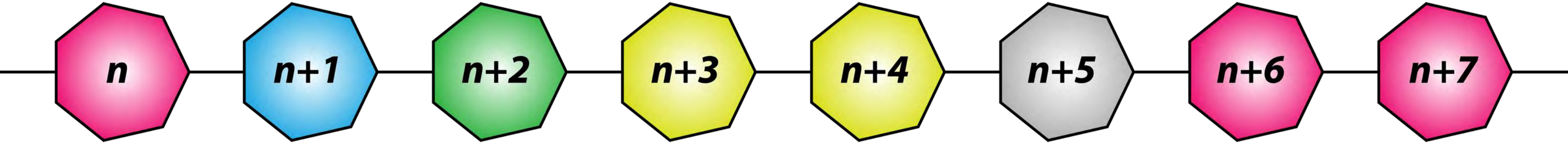
Nature recycles without overt accumulation

How can a butterfly be sustainable?

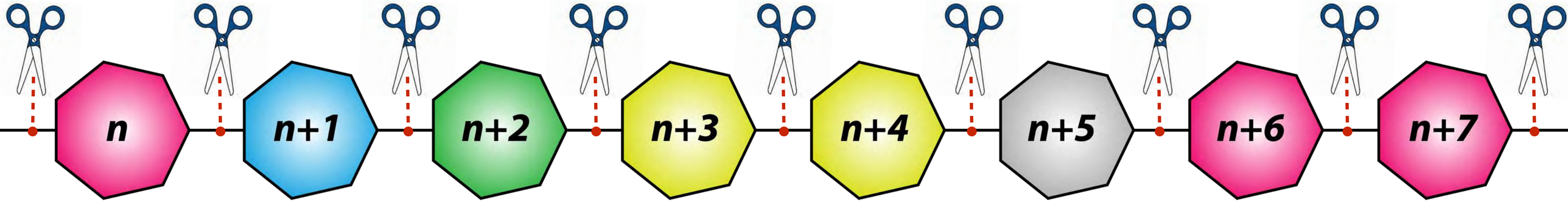
Proteins: sequence-defined (SD) natural polymers



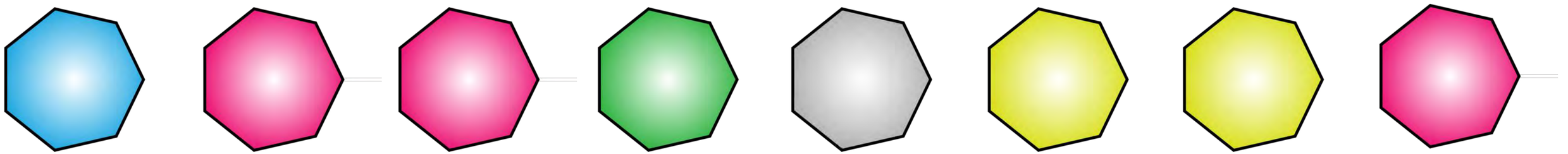
Digestion



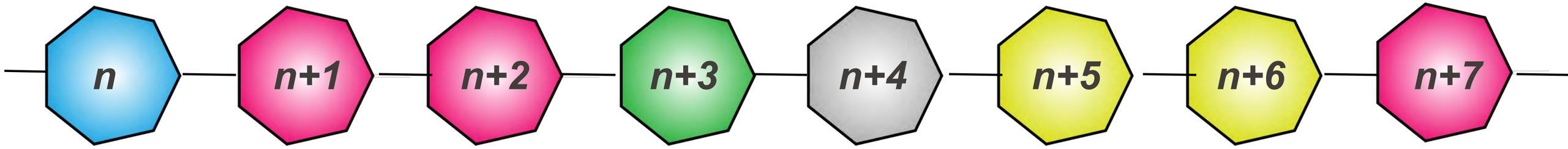
Digestion



Digestion

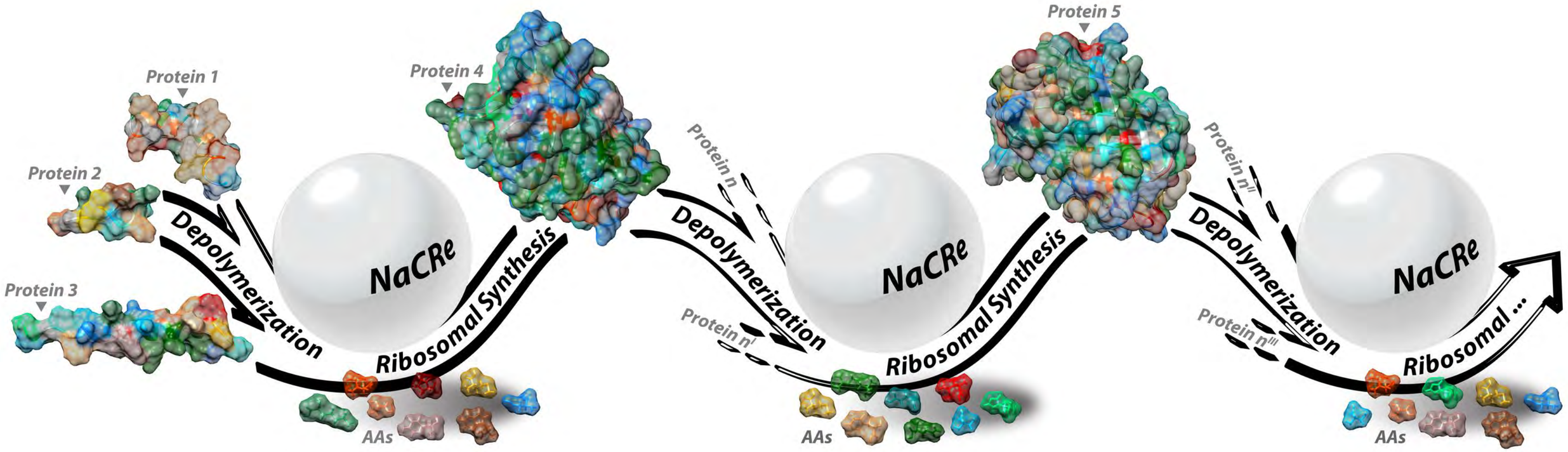


Ribosomal synthesis



Nature-inspired Circular-economy Recycling (NaCRe)

Proof of concept



Giaveri, S. *et al. Adv. Mater.* (2021)

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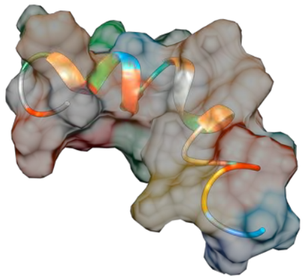
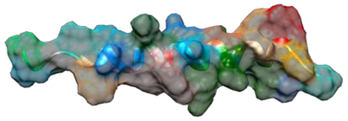
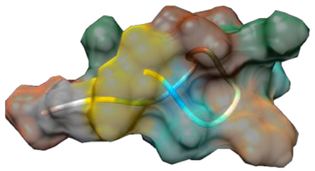
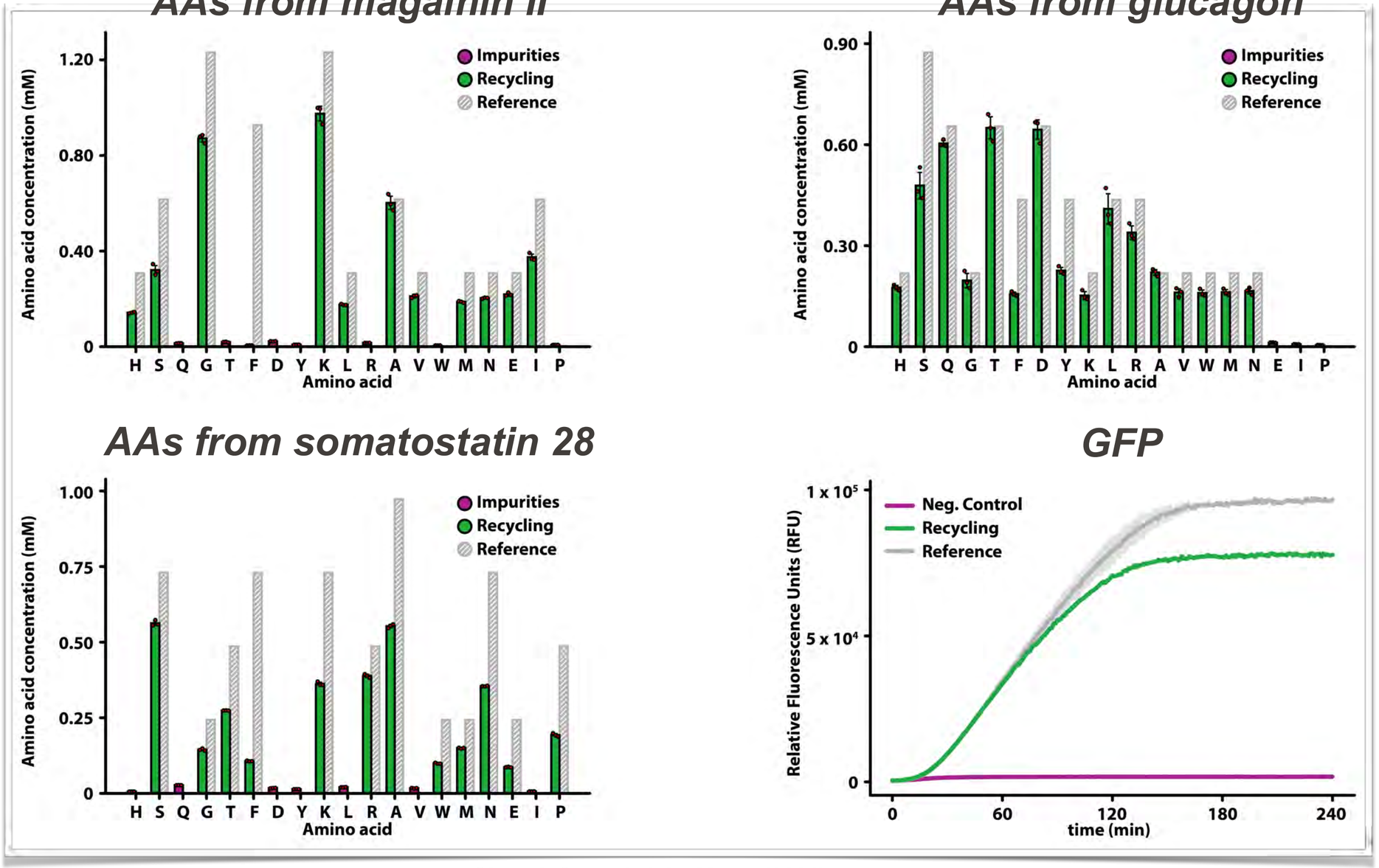
NaCRe: 3 peptides









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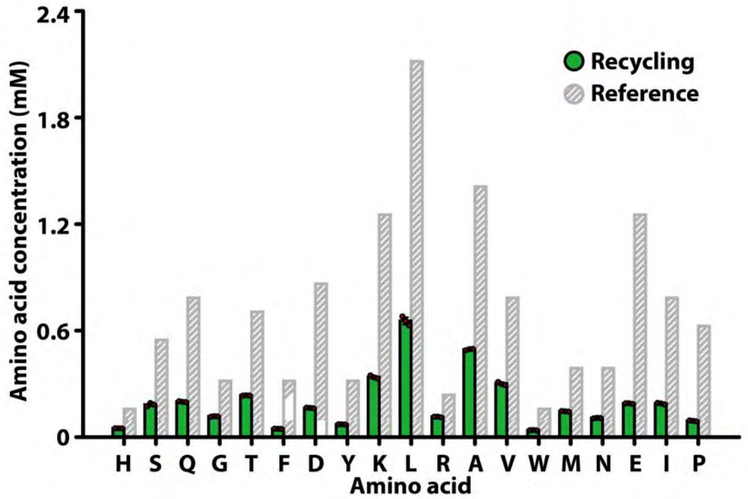
NaCRe: protein-based materials

AAs from β-lactoglobulin A



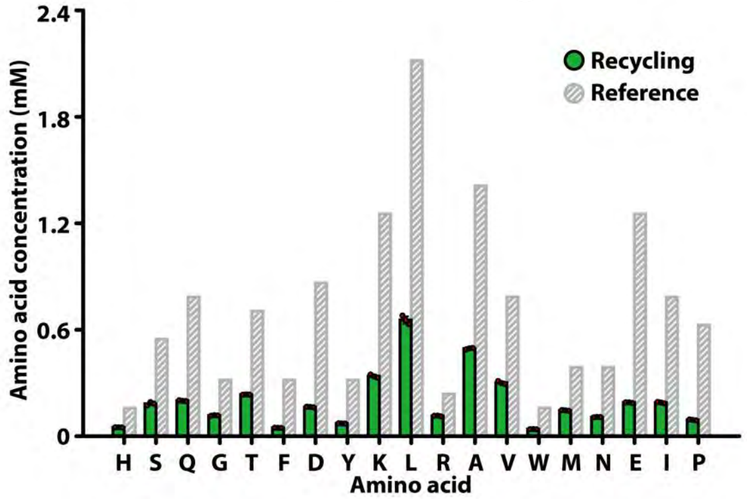
Filter (β-lactoglobulin amyloids)

In collaboration with Mezzenga's Lab (ETHZ)

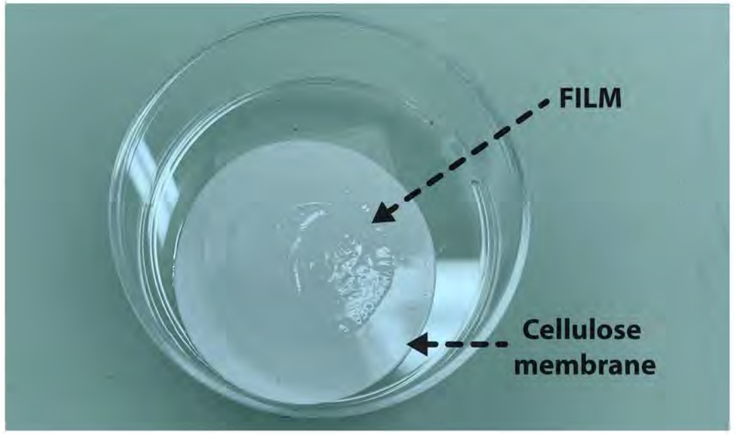
Giaveri, S. *et al. Adv. Mater.* (2021)

NaCRe: protein-based materials

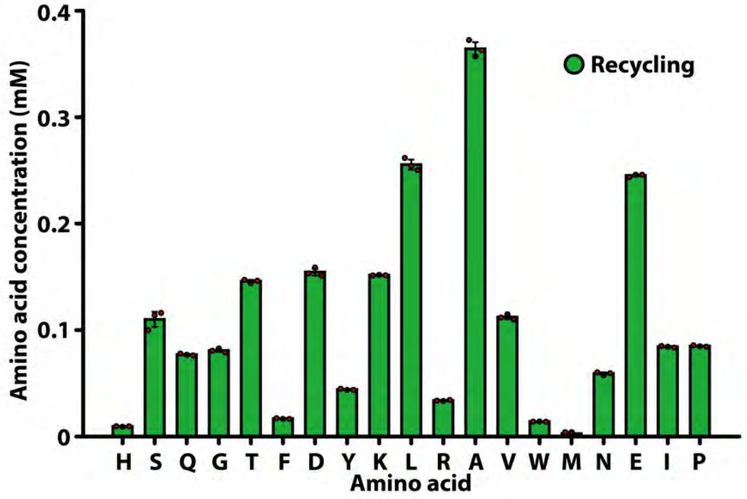
AAs from β-lactoglobulin A



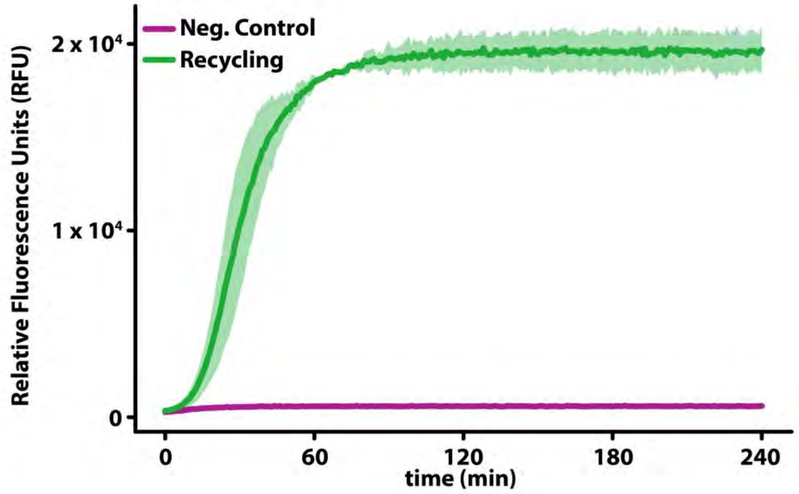
FILM (β-lactoglobulin amyloids)



AAs from the FILM

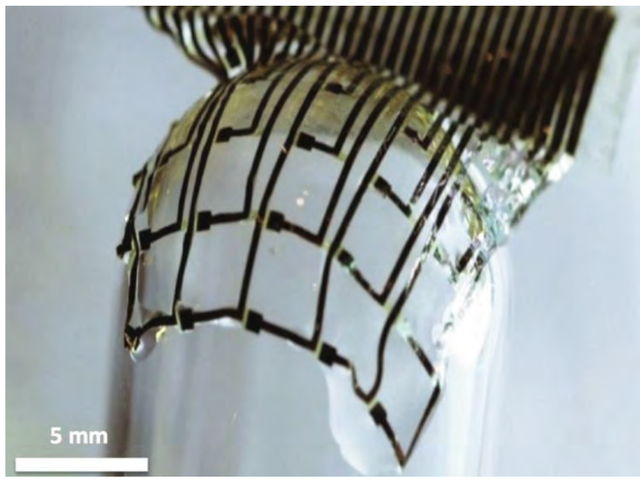


GFP



Giaveri, S. *et al. Adv. Mater.* (2021)

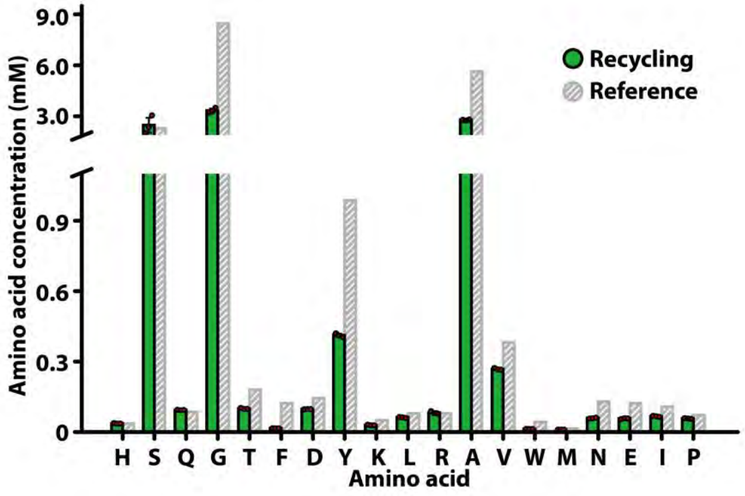
NaCRe: protein-based materials



Marelli, B. *et al. PNAS* (2017)

Tao, H. *et al. Adv. Mater.* (2012)

AAs from a silk solution



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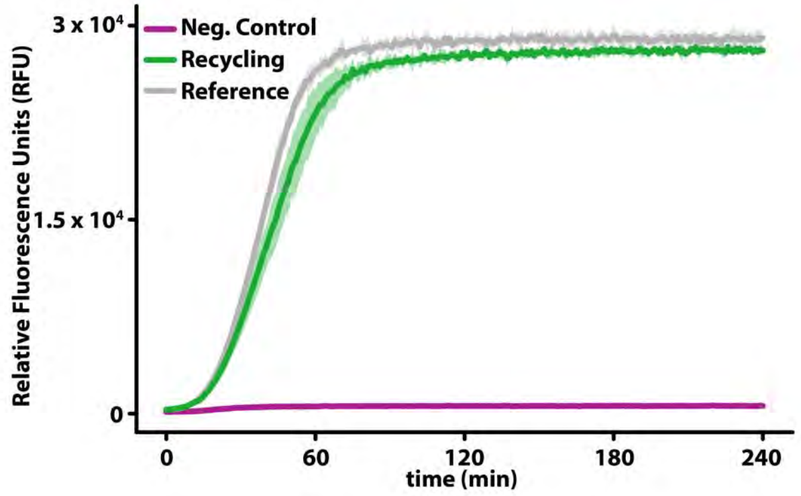
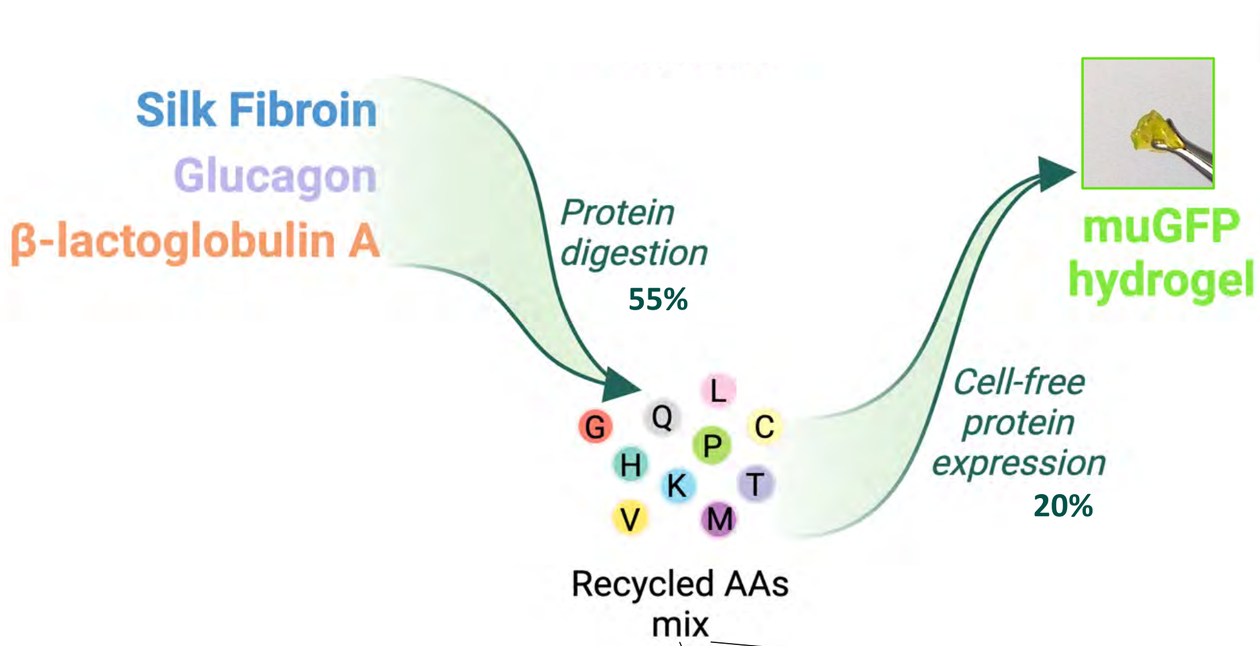
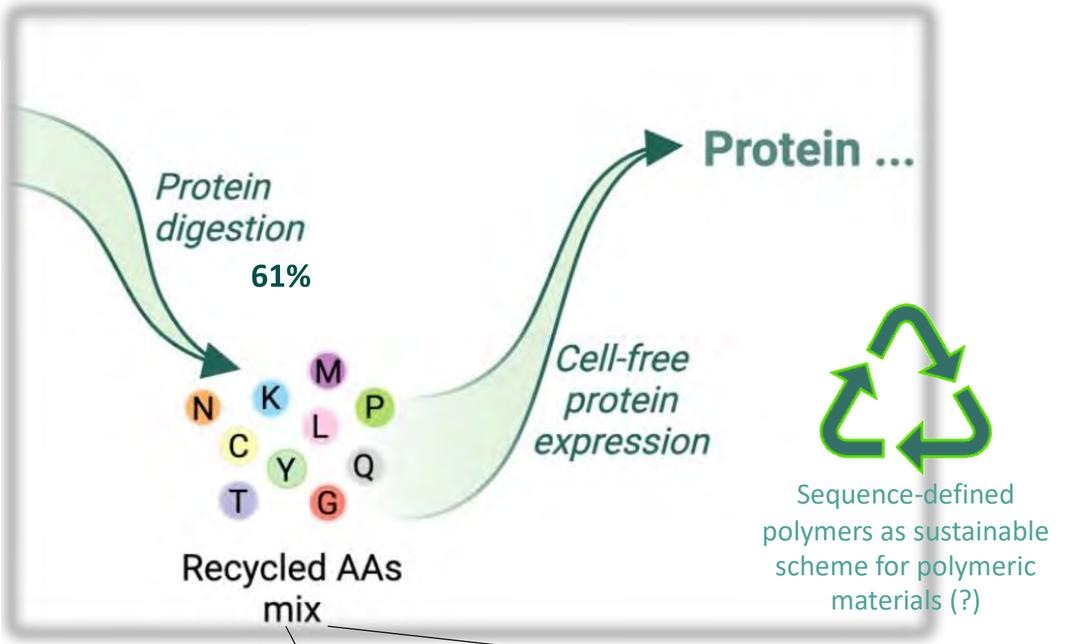


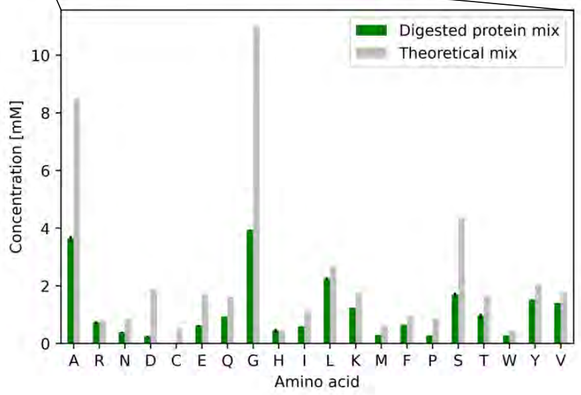
Giaveri, S. *et al. Adv. Mater.* (2021)

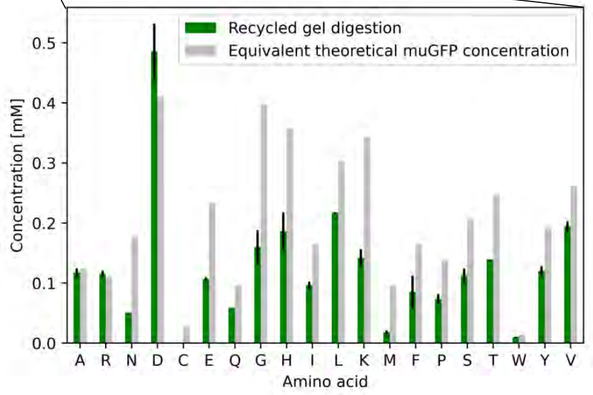
NaCRe: protein-based materials





HPLC-MSMS
Quantification of recycled AAs:





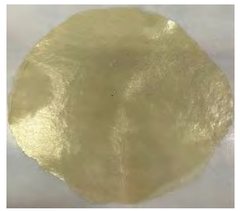
Laura Roset Julia *et al. RSc Sustain.* (2024)

The Potential of the Approach: Multilayers

Synthesis

Castor oil film

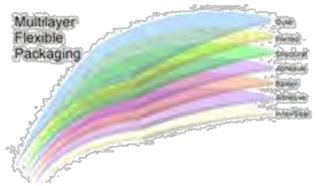
+

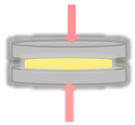


Gluten film

+

Castor oil film



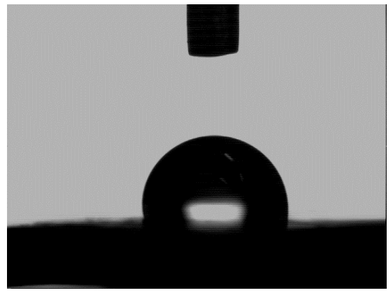


Hot press

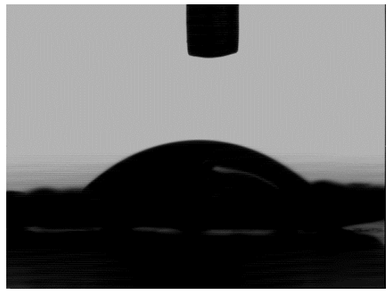
80 ℃,
60 kN,
20 min

Laminated film

Improved hydrophobicity

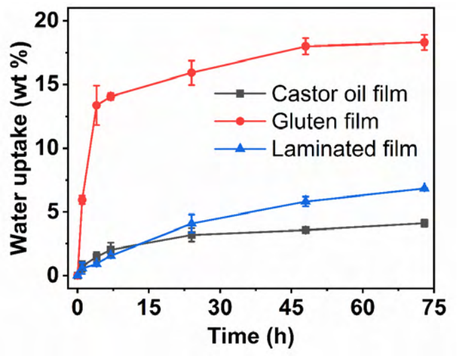


Laminated film

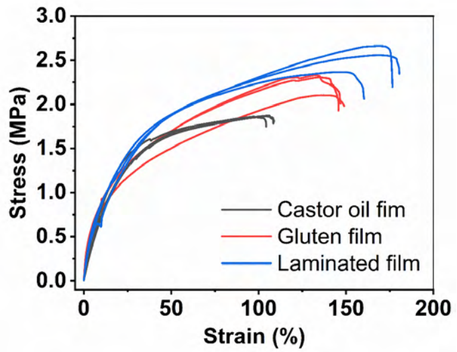


Gluten film

Improved moisture resistance and mechanical properties



Moisture absorbing

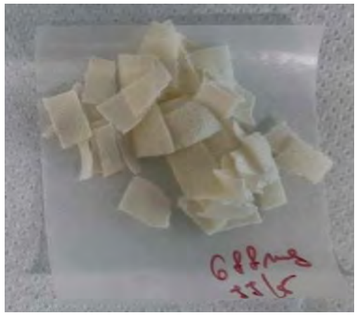


Tensile testing

Youwei Ma, in preparation

Short Term Solution: Digestion to Amino Acids

83% Merino wool + 17% Nylon



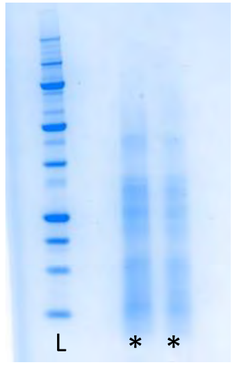
Dissolution for recovery of protein

Recovered Nylon

Recovered Wool protein (Regenerated keratins)

Keratin dissolution

** Dissolved keratin from merino wool Tshirt*
L: Protein ladder



Amino acids for NaCRe

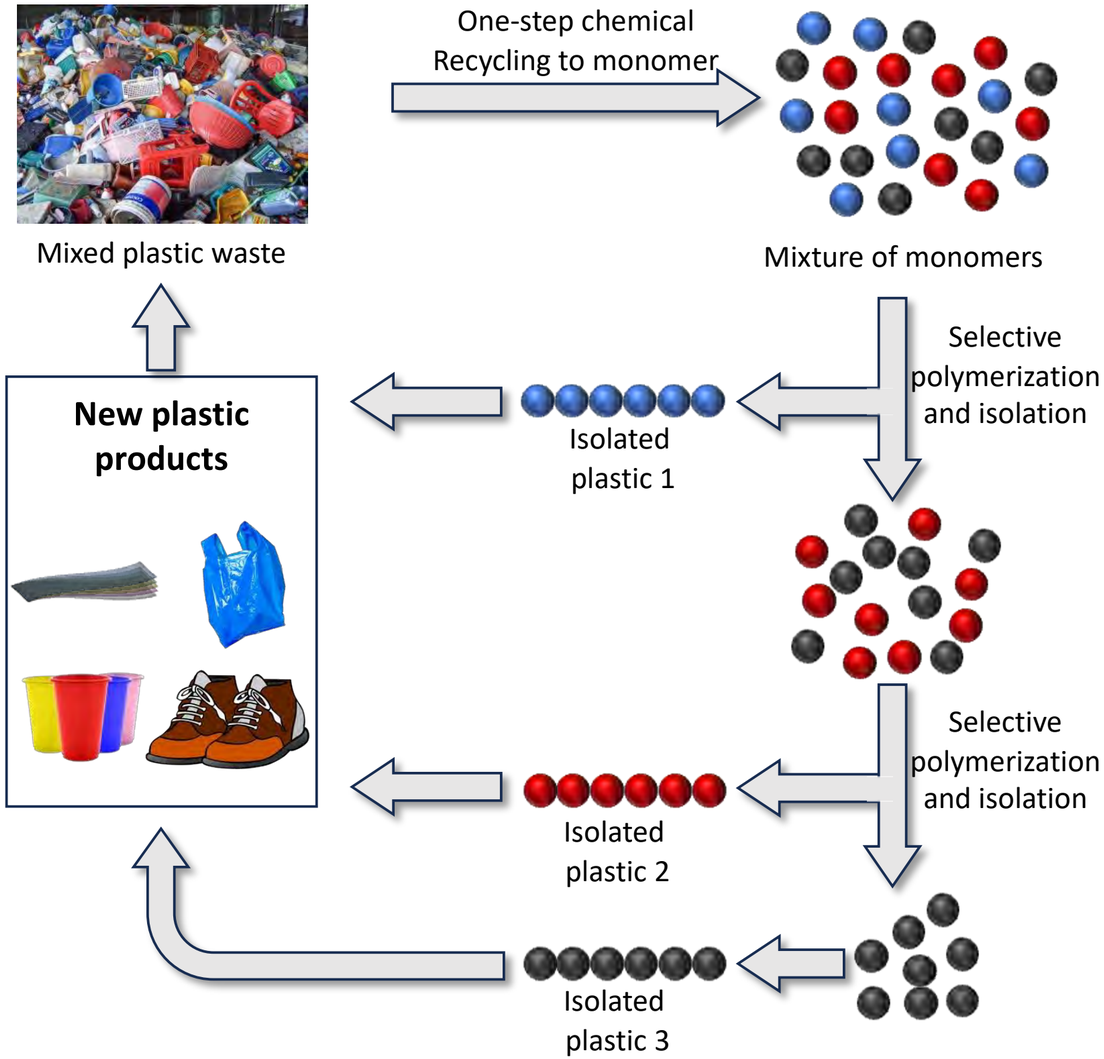
Keratin bioplastic

Others….

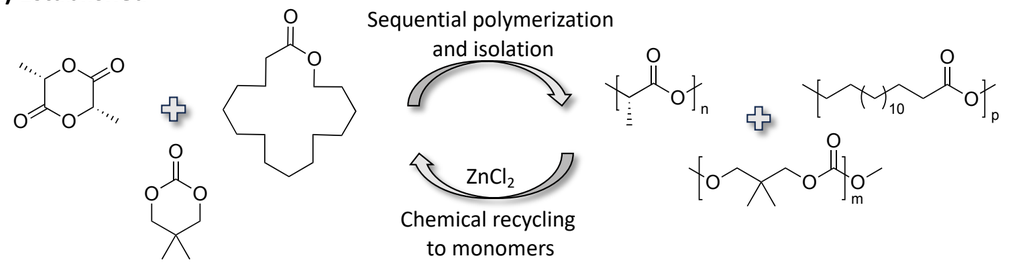
Laura Roset Julia and Ivana Ivancova, in preparation

Short Term Solution: Digestion to Amino Acids

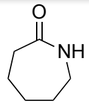
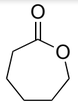
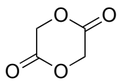
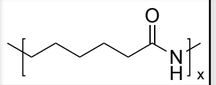
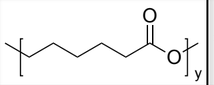
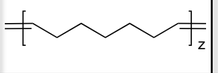
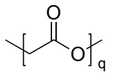
Mixed **P**lastic **D**epolymerization-**S**equential **S**elective **P**olymerization (**MPD-SPP**)



(A) Established



(B) Proposed additional monomers and polymers

Name	Caprolactam	Caprolactone	Cycloheptene	Glycolide
Monomer structure				
Polymer structure				
Polymerization mechanism	Anionic ring opening polymerization	Ring opening polymerization	Ring opening metathesis polymerization	Ring opening polymerization

Gadi Slor, in preparation

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Conclusions

Plastics is a Difficult Problem,
but Proteins can help.

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Acknowledgments

FNSNF
Swiss National Science Foundation

BIO-INSPIRED MATERIALS
NATIONAL CENTER OF COMPETENCE IN RESEARCH

NCCR
Molecular Systems Engineering

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

FONDATION LEENAARDS

Nestlé

WSS
WERNER SIEMENS-STIFTUNG

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

erc
European Research Council
Established by the European Commission