School of Engineering

Civil and Environmental Engineering

Structural Biopolymers: using Nature's building blocks as an inspiration for advanced manufacturing

Benedetto Marelli, Laboratory for Advanced Biopolymers, CEE @ MIT

Biomaterials tomorrow

bio-instructive
respond to their surroundings
transform themselves
disappear harmlessly
biocompatible without sacrificing technological performance
have "non-obvious" functions

2017 MIT Research and Development Conference - November 16, 2017

Brief Bio

Benedetto Marelli

Paul M. Cook Career Development Professor
Civil and Environmental Engineering – MIT

B.Eng. – Biomedical Engineering – Politecnico di Milano ('05)

M.Sc. – Biomedical Engineering – Politecnico di Milano ('08)

Ph.D. – Materials Science and Eng. – McGill University ('12)

Postdoc – Biomedical Engineering – Tufts University

Laboratory for Advanced Biopolymers | L.A.B.

Structural biopolymers synthesis, assembly and fabrication

Materials for agriculture, food safety and food security

Materials for regenerative medicine, sensors and optoelectronics

Soil Engineering

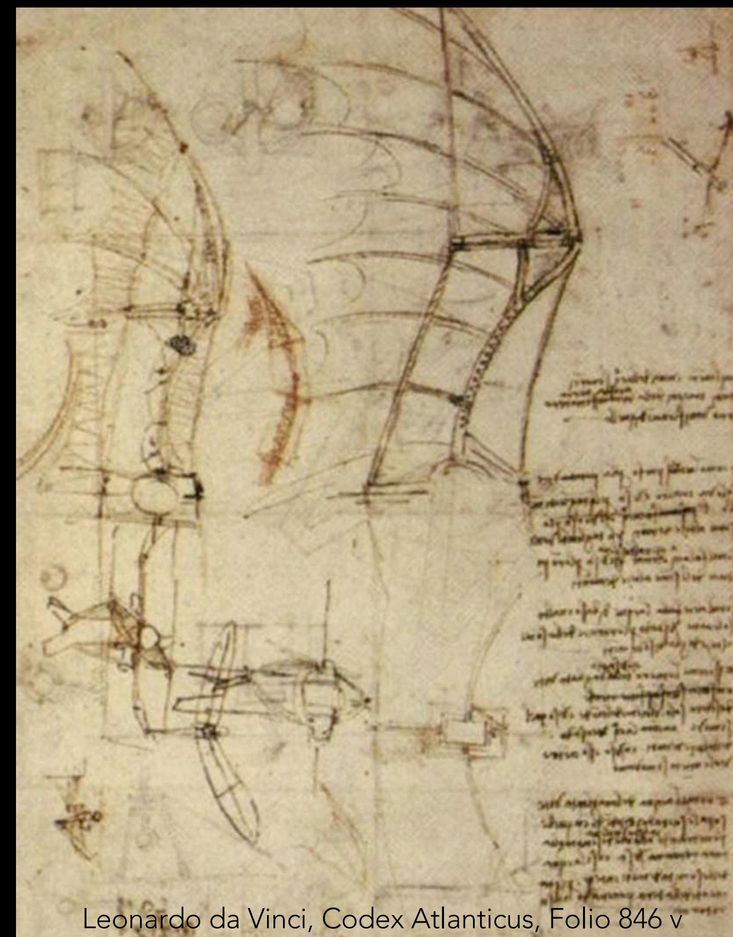
Massachusetts Institute of Technology

Civil and Environmental Engineering

Nature as source of inspiration

From mythology…

Daedalus and Icarus, Charles Paul Landon



Leonardo da Vinci, Codex Atlanticus, Folio 846 v

…to the study of innovative solutions

Nature as source of inspiration for engineering innovative solutions…

Shinkansen train nose

Kingfisher's beak

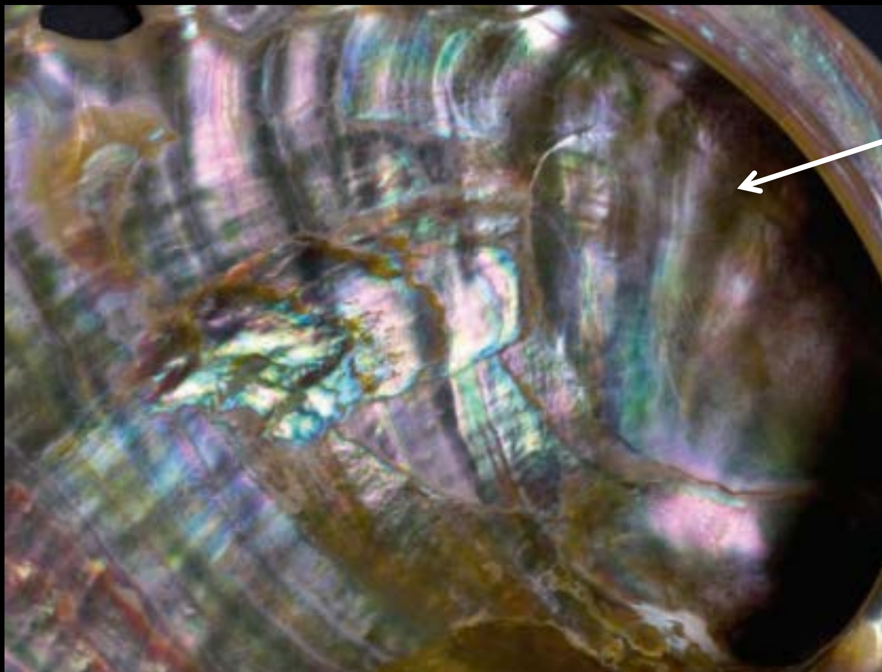
Bioinspiration
Biomimicry

Falcon wing feather

Thermal chimneys

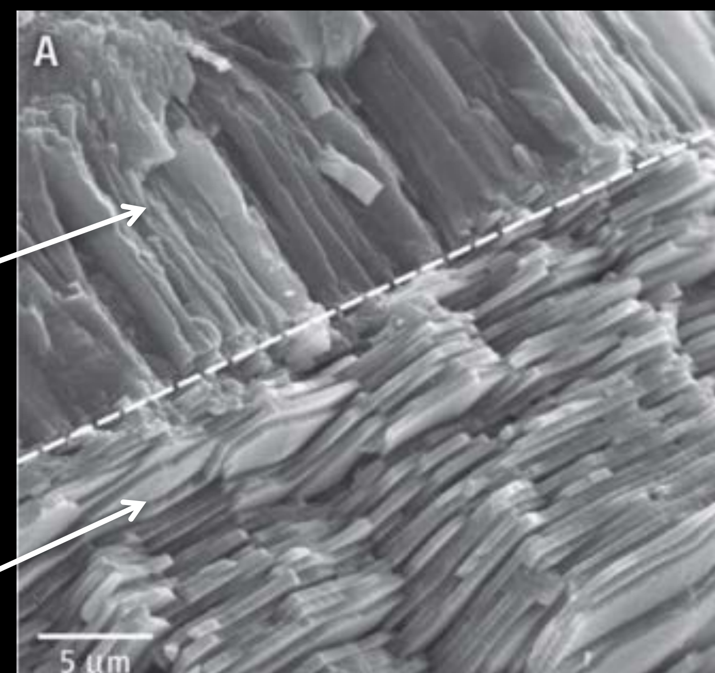
P.-Y. Chen et al. / Progress in Materials Science 57 ,1492–1704 , (2012)

Nature as source of inspiration for engineering innovative solutions…



Fractured mollusk shell

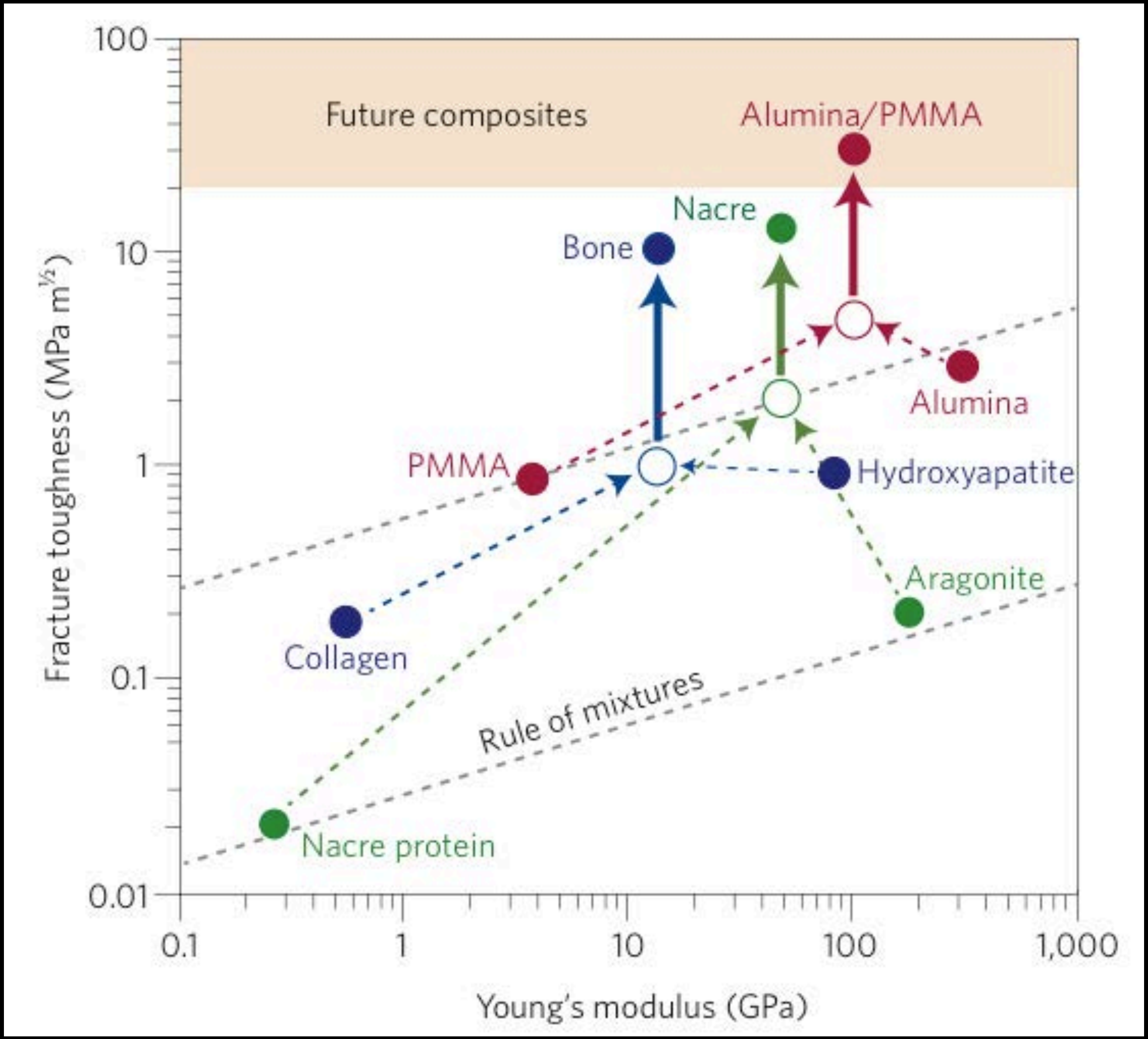
Prismatic calcite



Nacre

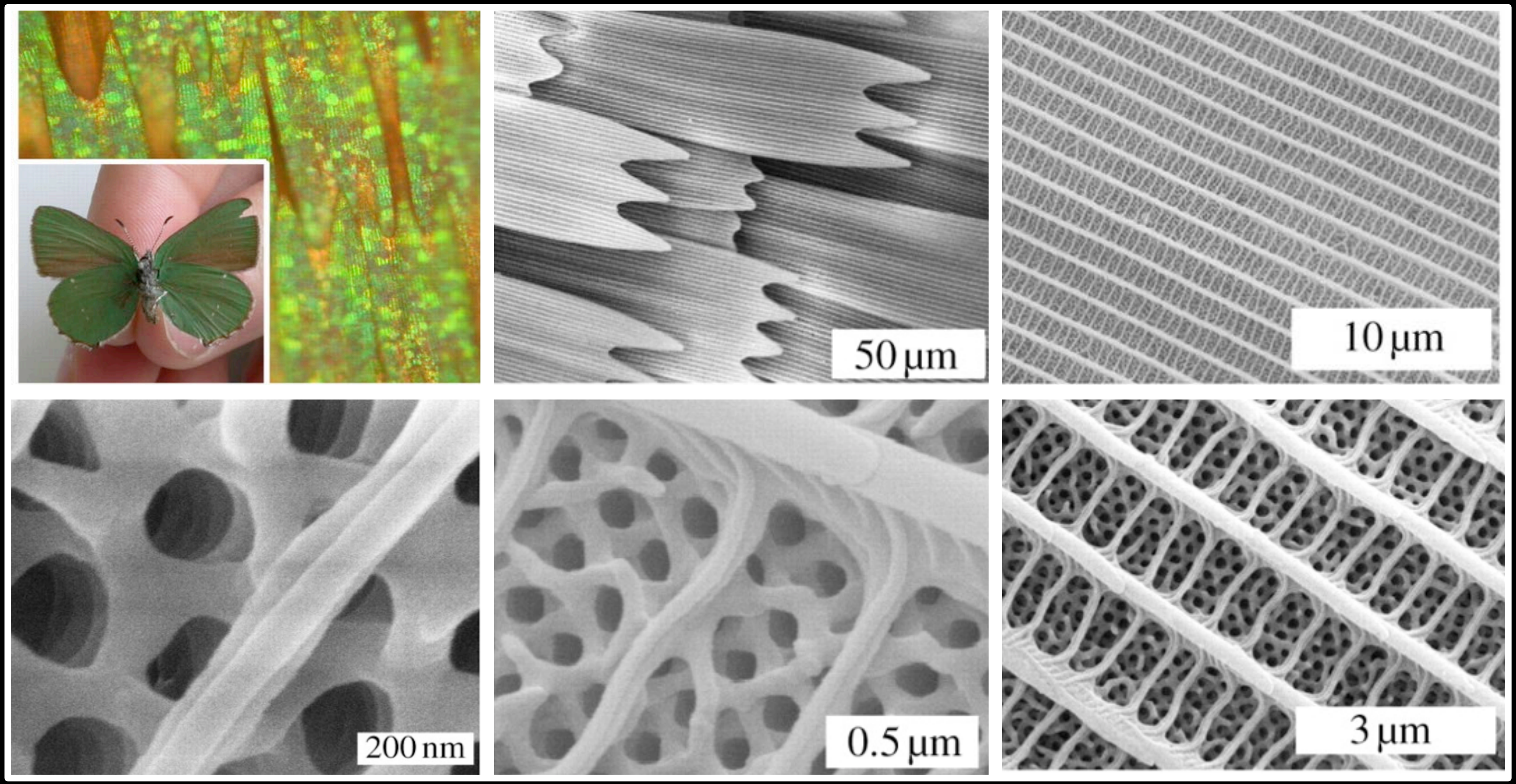
Kröger, Science, 325, 1351-1352, (2009)

Nature as source of inspiration for engineering innovative solutions…



Adapted from Munch et al., Science, 322, 1516-1520 (2008) and Wegst et al Nat Mater 14, 23–36 (2015)

Nature as source of inspiration for engineering innovative solutions…



Schröder-Turk et al J Struct Biol 174(2), 290-295 (2011)
Michielsen et al, Interface 5, 85-94 (2010)

Structural biopolymers are the building materials of life – they realize a diversity of functions that provide structural support, locomotion and protection

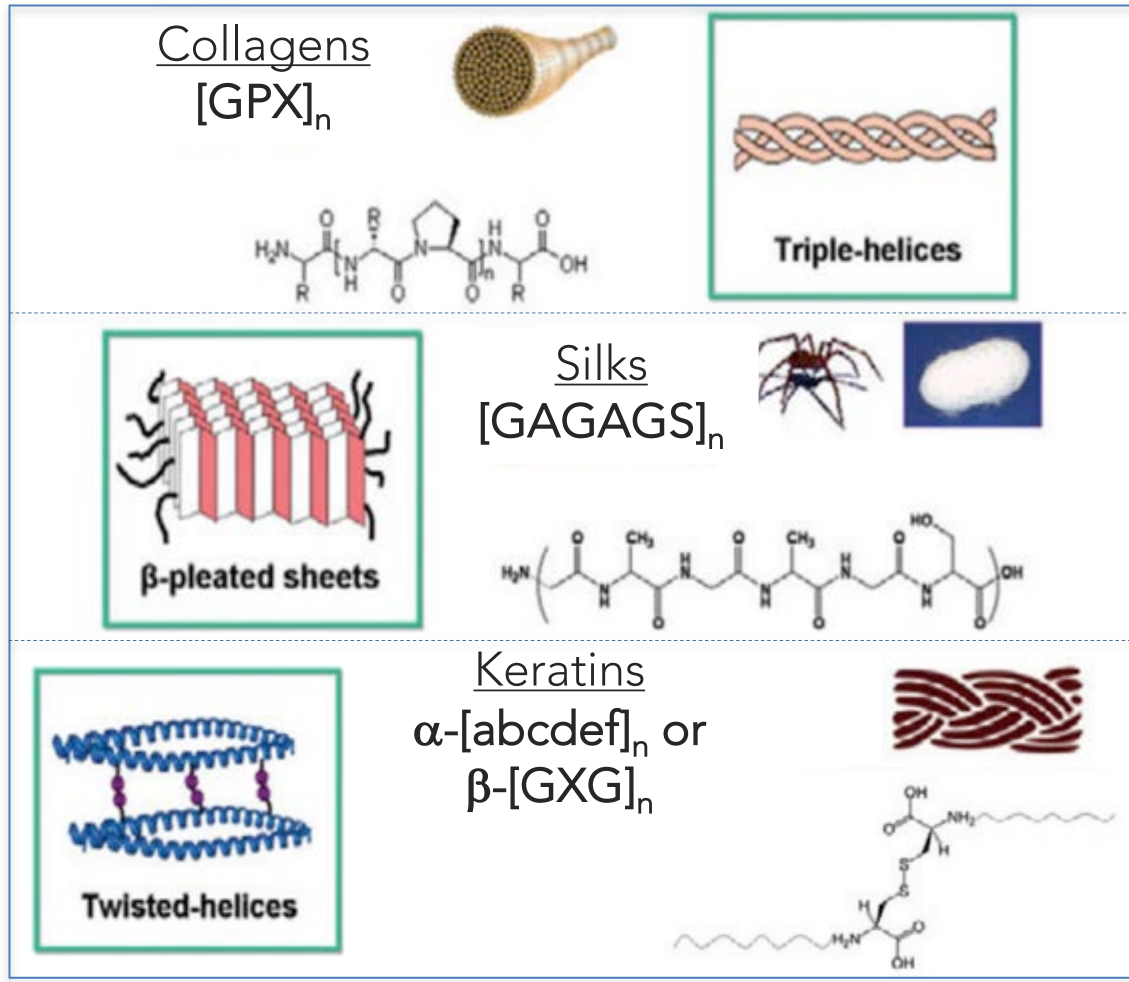
Key features:

i. Simple material makeup developed to facilitate species survival

ii. Materials efficiently created with low energy consumption

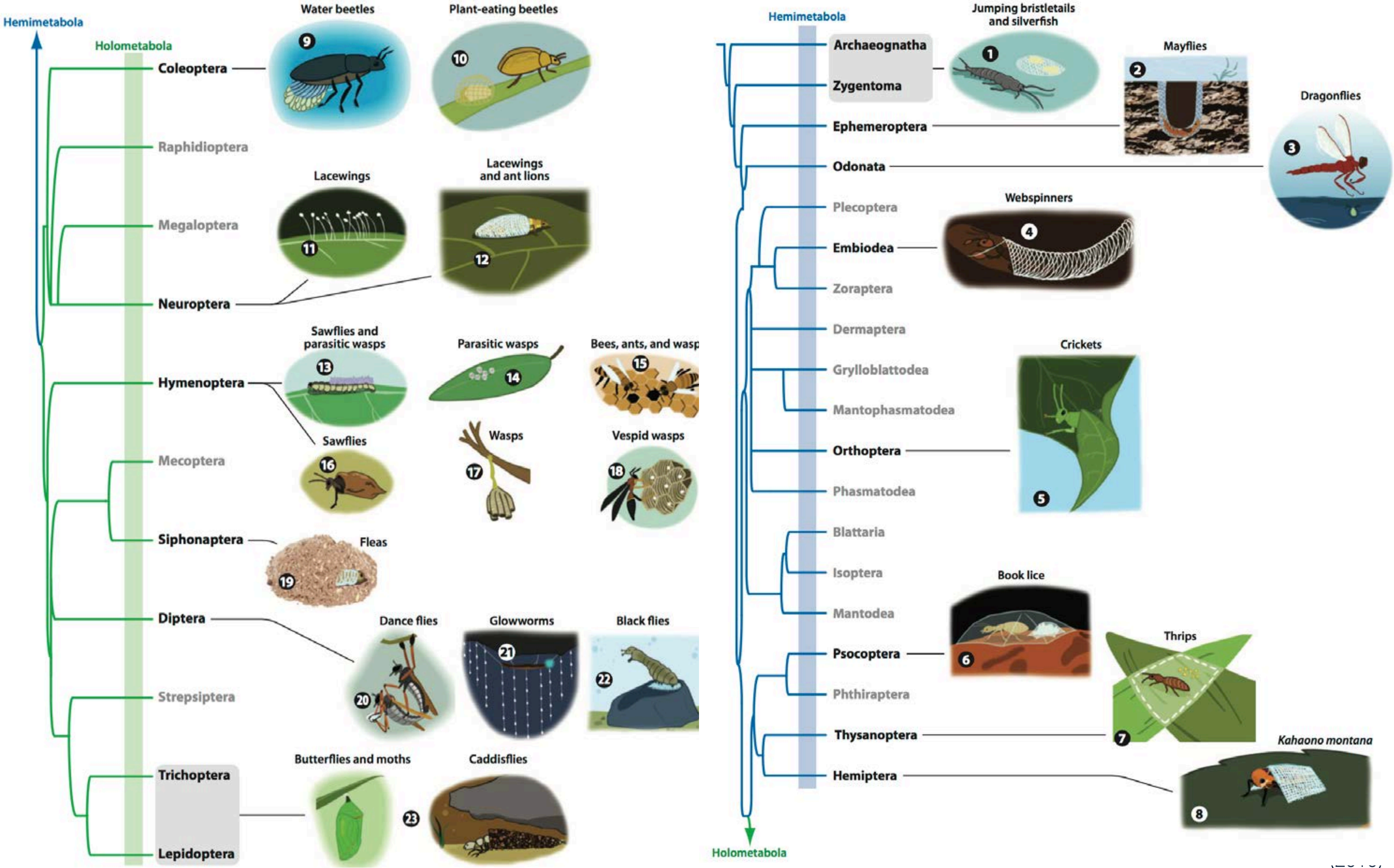
iii. Simple processing conditions

iv. Formed from a few distinct but abundantly available repeating material constituents



Hu et al. Mater Today 15(5),208–215 (2012)

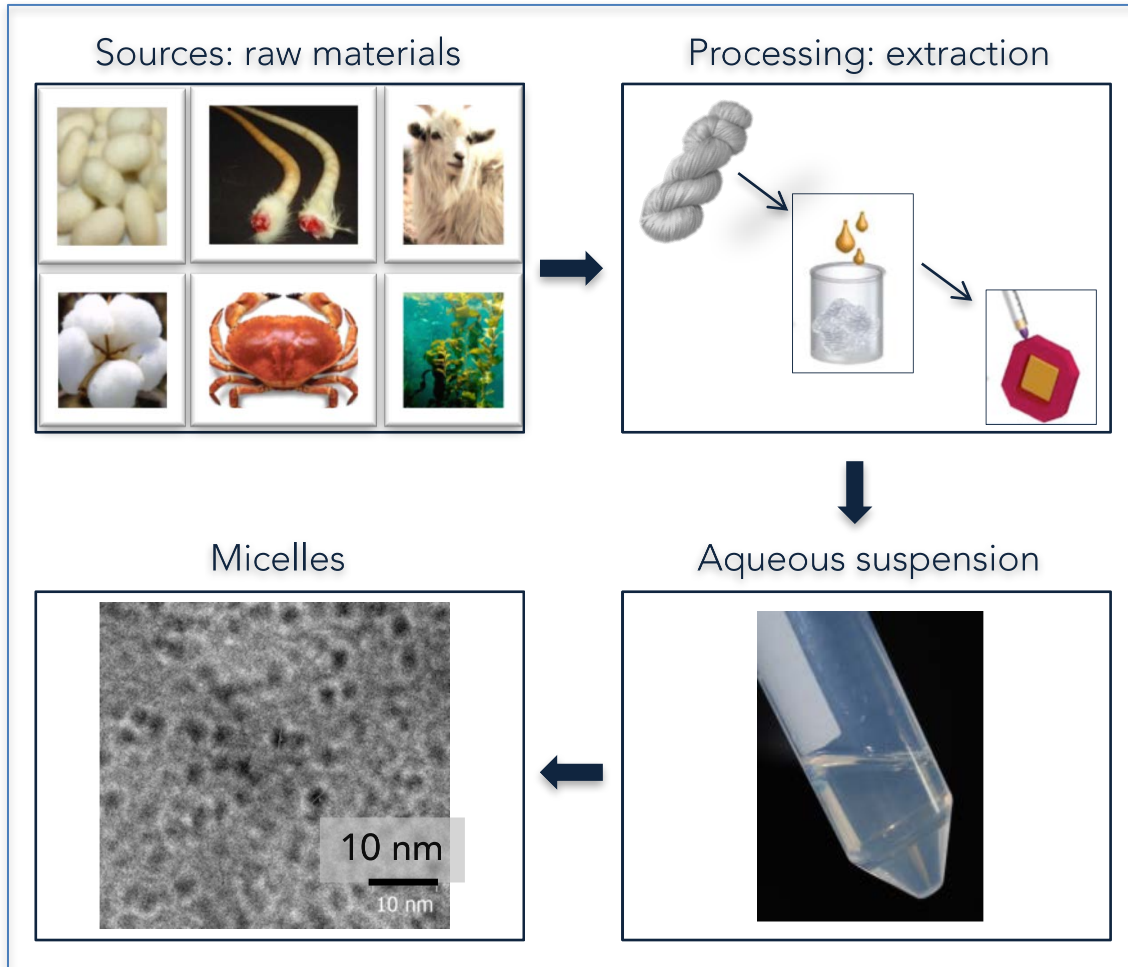

Insect Silk: One Name, Many Materials



Biopolymers can be regenerated to their molecular form – the reverse engineering process yields aqueous suspensions where the biomolecules are in a state similar to the extracellular one

Engineering design:

i. Regeneration in aqueous *solutions*



Assembly of silk materials

Key features:

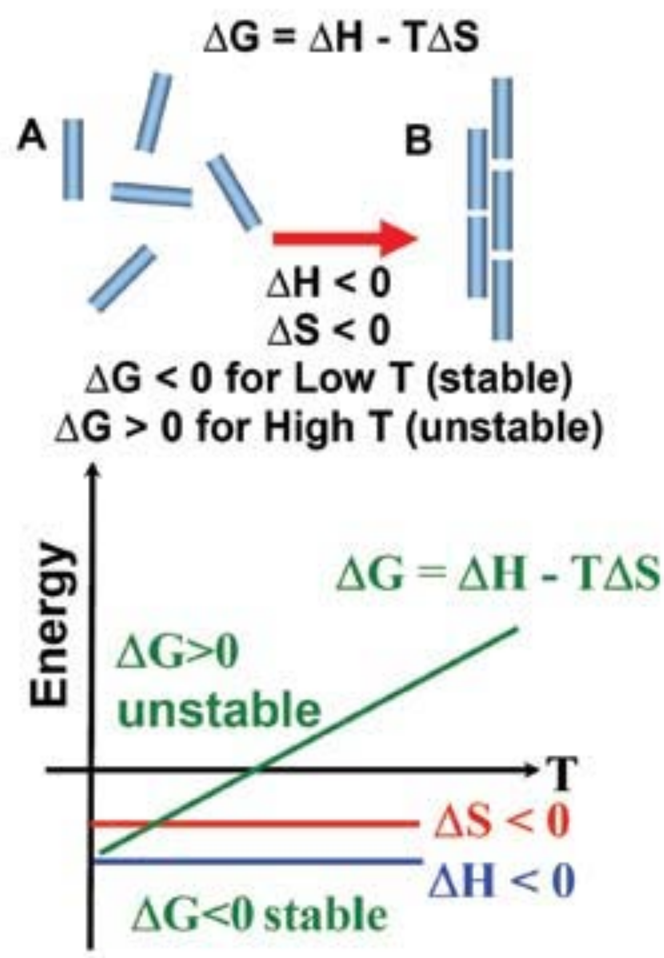
i. Low-energy processing

ii. Mild environments

iii. Self-assembly

iv. Polymorphism

Thermodynamics of self-assembly



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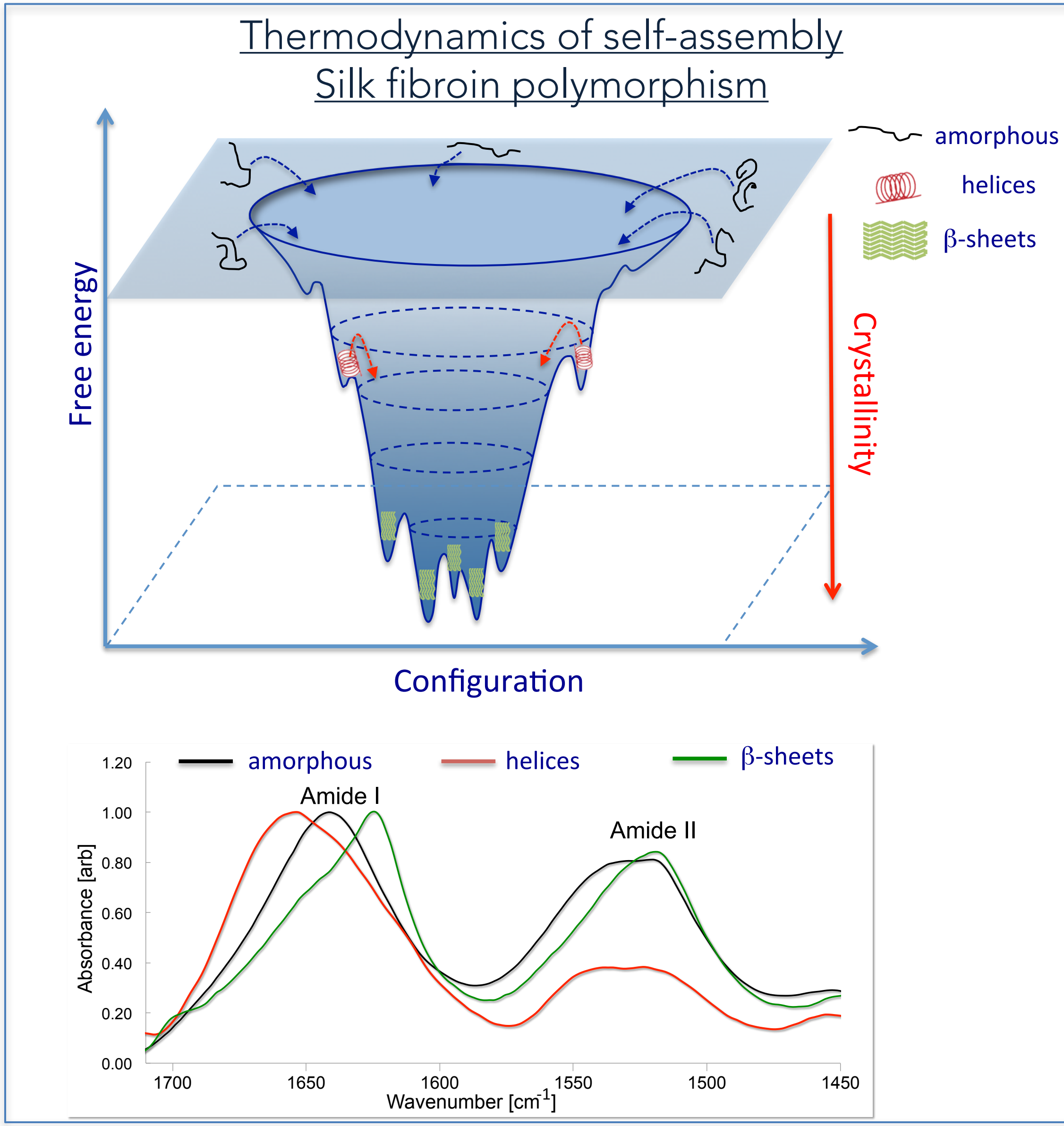

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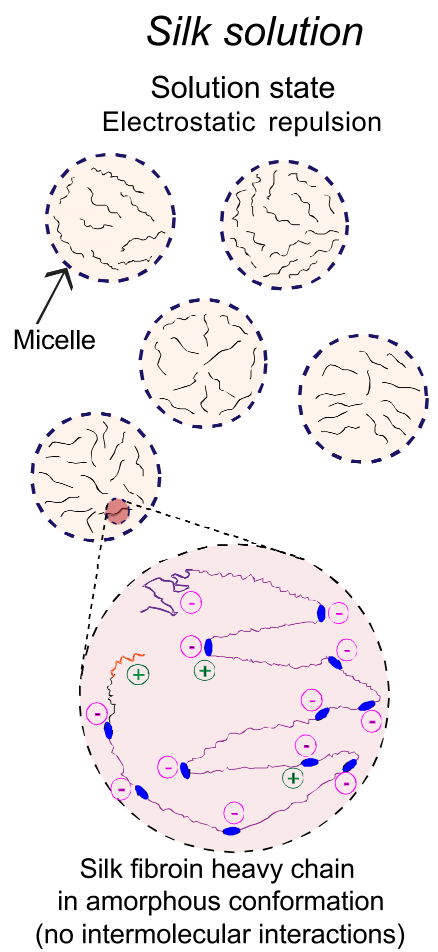
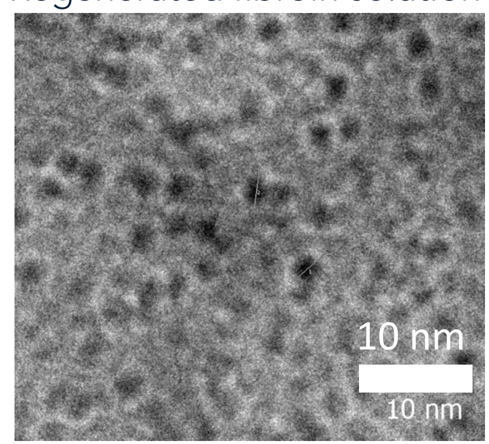
Marelli et al, PNAS 2017

Silk fibroin self-assembly



Regenerated fibroin solution



Assembly of silk materials

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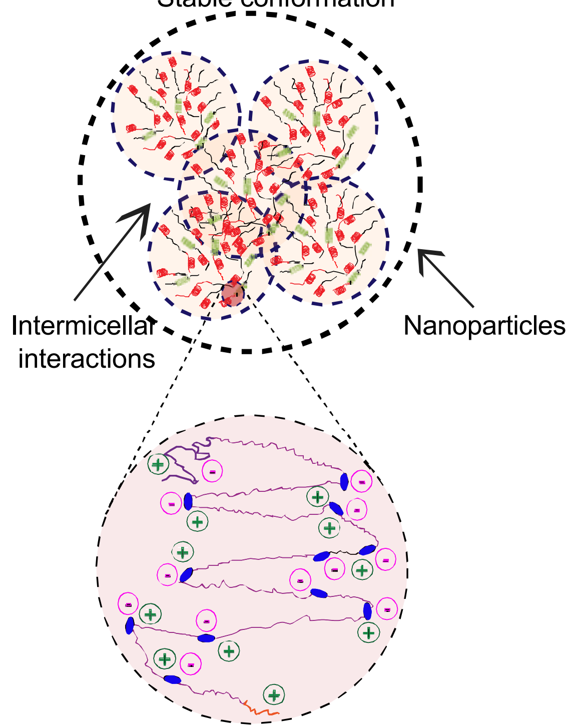
Marelli et al, PNAS 2017

Silk fibroin self-assembly

Silk hydrogel

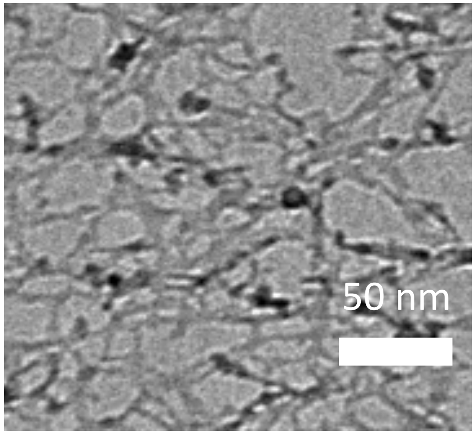
Intermolecular interactions

Stable conformation



Silk fibroin heavy chain in helical and beta-sheet conformation (intermolecular interactions and crosslinks)

Regenerated fibroin gel



Assembly of silk materials

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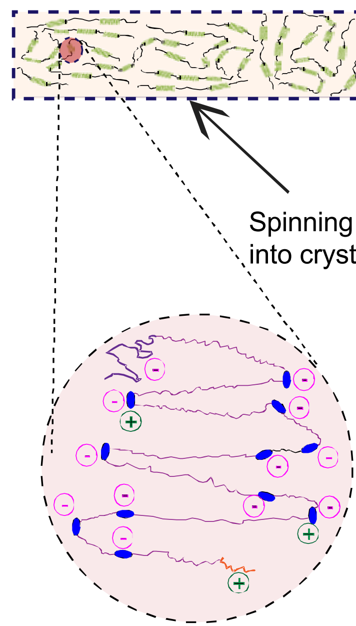
Marelli et al, PNAS 2017

Silk fibroin self-assembly

Silk monolith

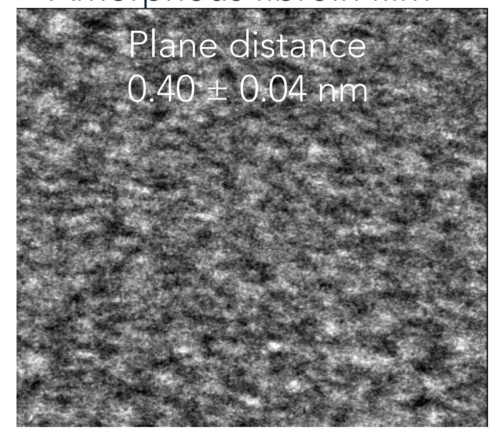
Intermolecular crosslinks
Stable conformation



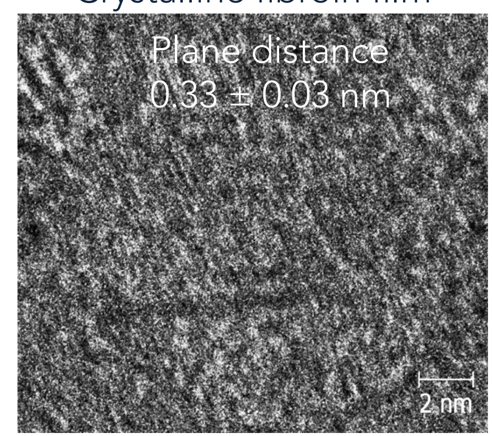
Spinning silk nanoparticles into crystalline nanofibrils

Silk fibroin heavy chain in beta-sheet conformation (intermolecular crosslinks)

Amorphous fibroin film



Crystalline fibroin film



Biopolymers self-assembly is driven by modulating the molecular concentration in the suspension and environmental conditions – biological entities can be added at the point of self-assembly

Engineering design:

i. Regeneration in aqueous *solutions*

ii. Self-assembly in physiological conditions

Key: addition of dopants enables the formation of biopolymers-based materials with programmable functions

Biopolymer suspension

Addition of *dopants*

Cells, enzymes, GFs, antibodies, …

Self-assembly

Water removal, pH, T, P, shear stress, electric field,

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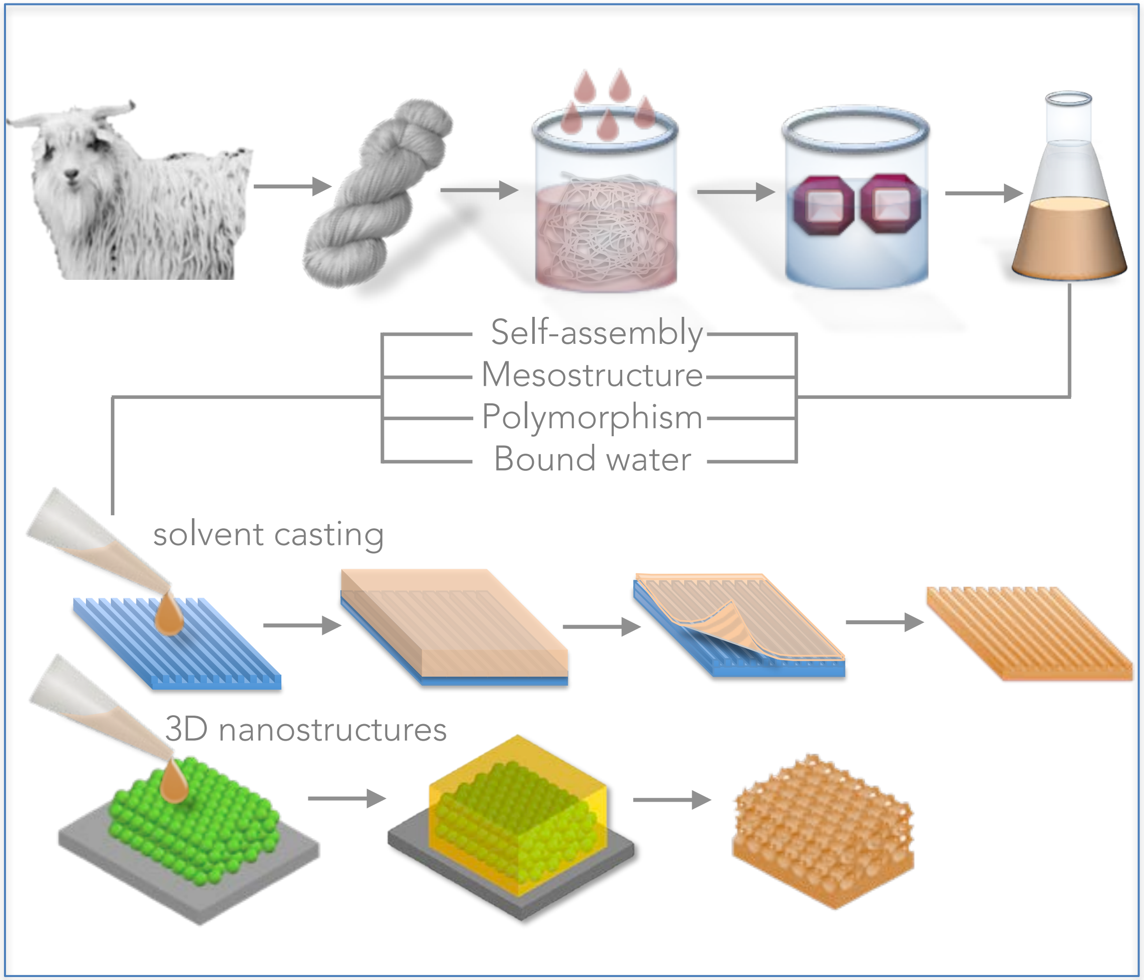
Regenerated biopolymers can be used as fundamental building blocks to address unmet technological challenges in regenerative medicine and advanced manufacturing

Key features:

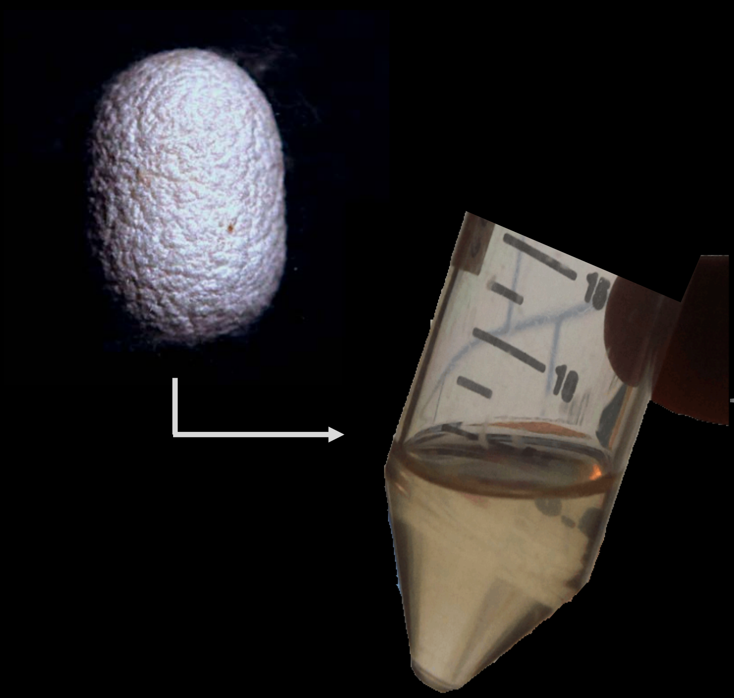
sustainable
processed in water
controlled degradation
edible
non-toxic
implantable
technological
preserves bio-function

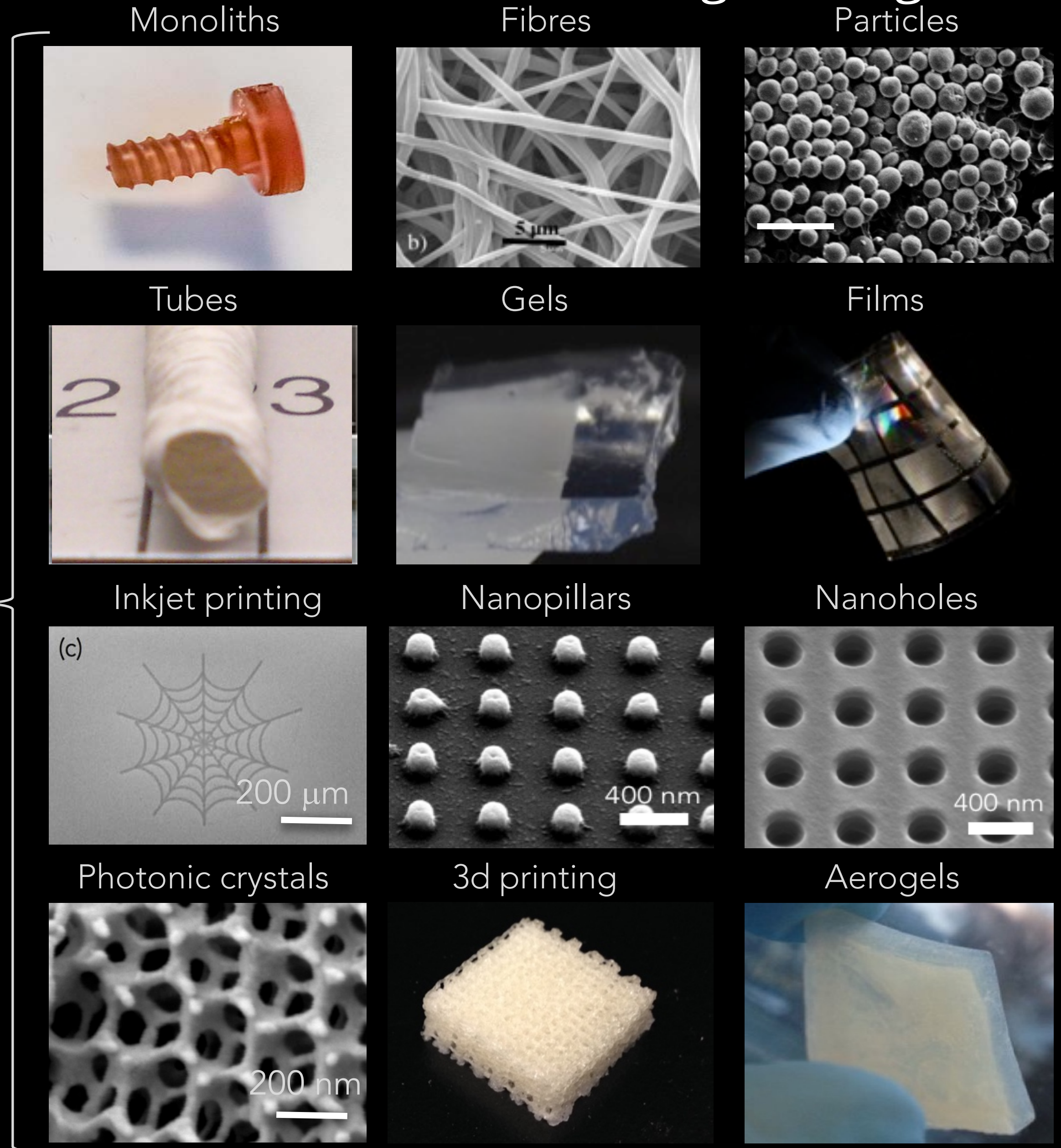


Marelli and Omenetto *J. Mater. Chem. C* 3, 2783-2787 (2015)

Forms and Functions

<u>Material form</u>: the silk protein can be fabricated in multiple formats that can be combined to orchestrate the engineering of materials with multiple functions in a single material format





Inkjet printing of silk fibroin: from printable forms to printable functions

Key features:

i. Unprecedented versatility

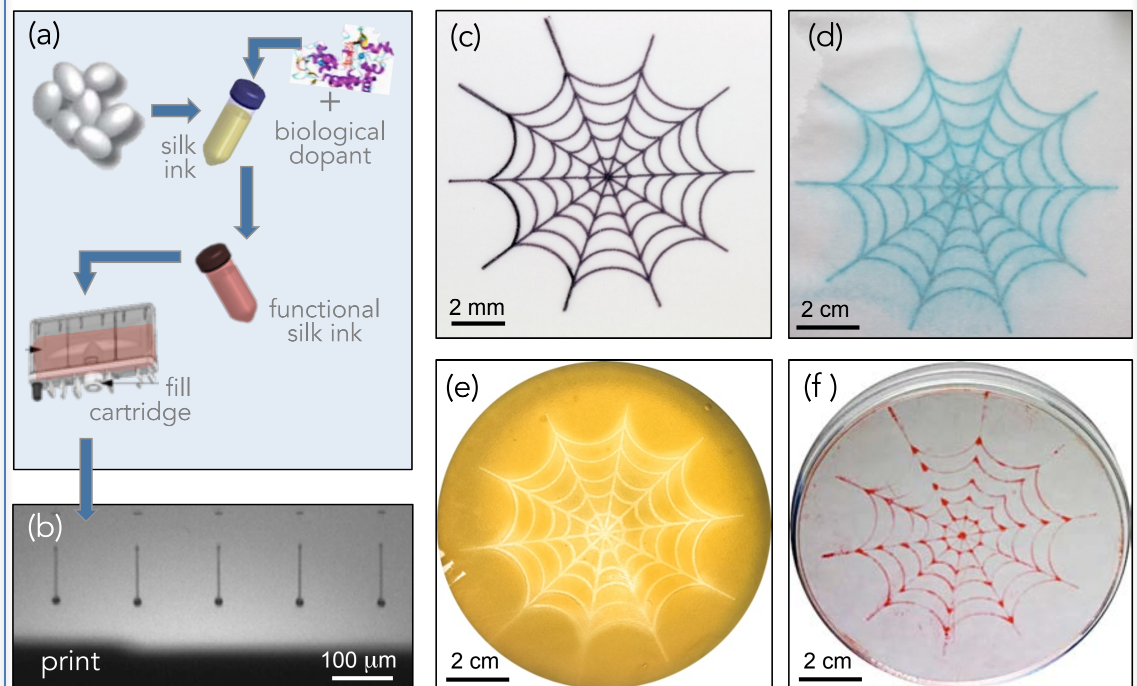
ii. Biotic/abiotic interface

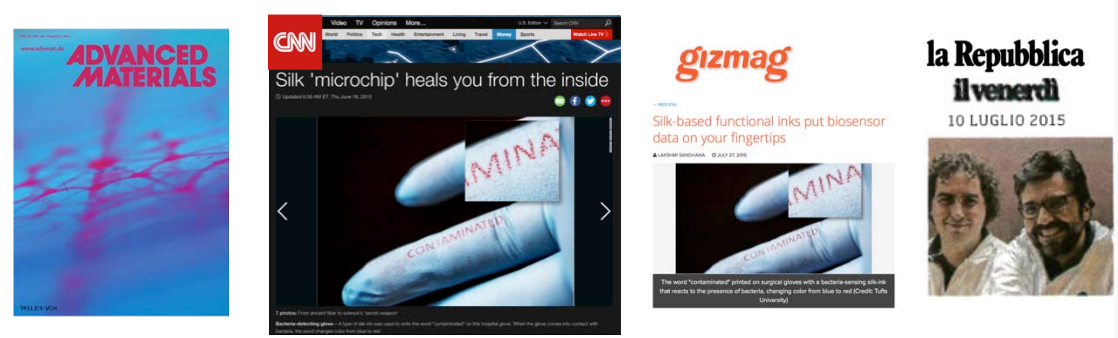
i. Biodegradable/compostable

ii. Organic/inorganic interface

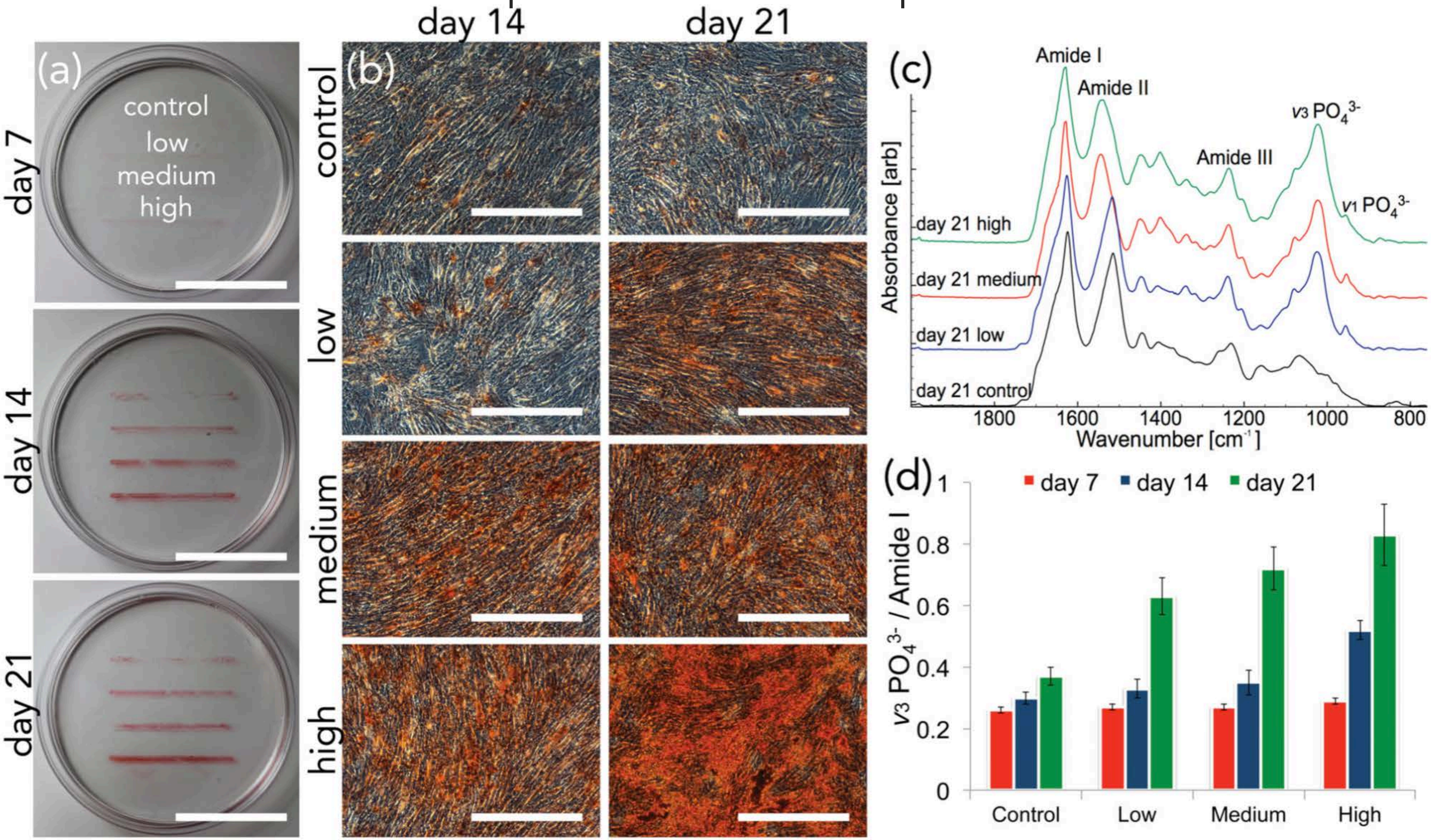
Marelli, Tao et al, Adv. Mater., 2015

Silk fibroin polymorphism



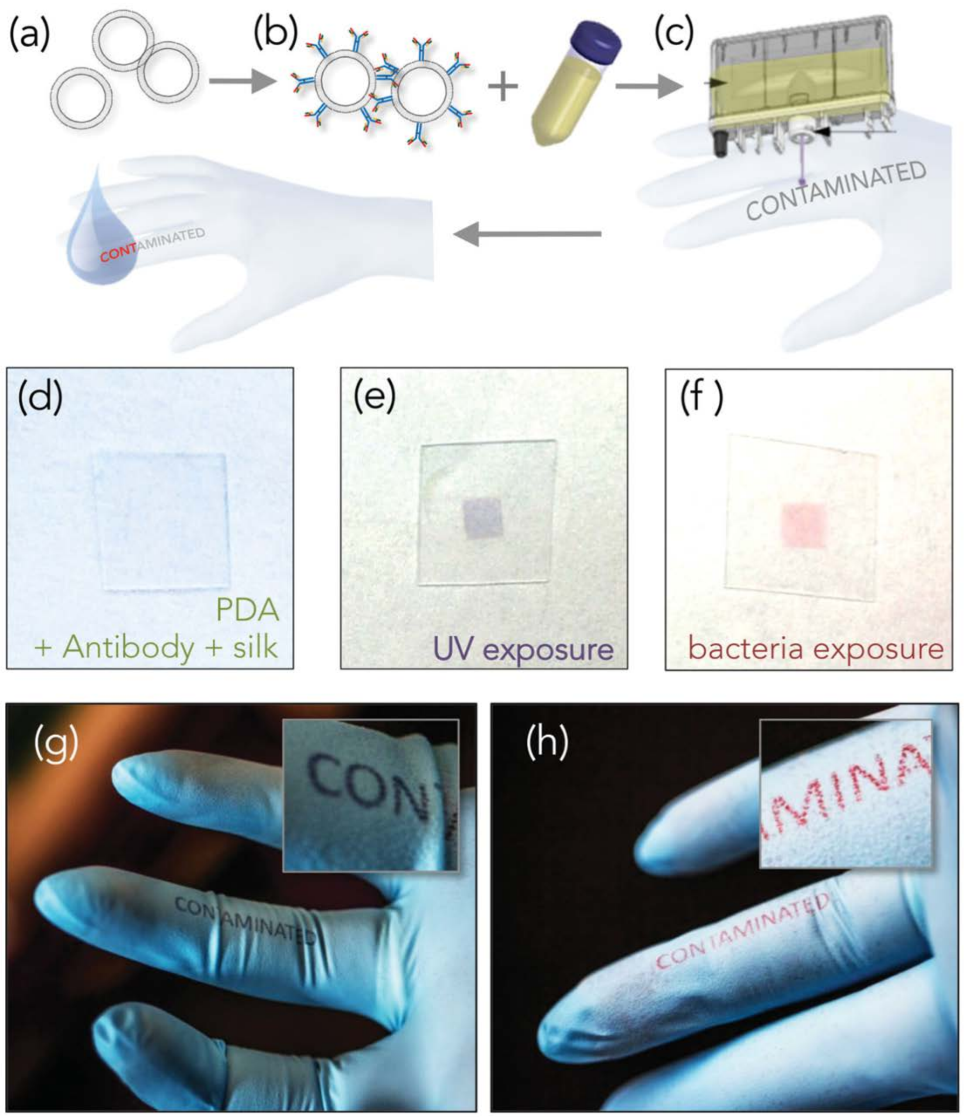


IJP of silk fibroin: From printable forms to printable functions



Tao, Marelli et al, Adv. Mater., 2015

IJP of silk fibroin: From printable forms to printable functions



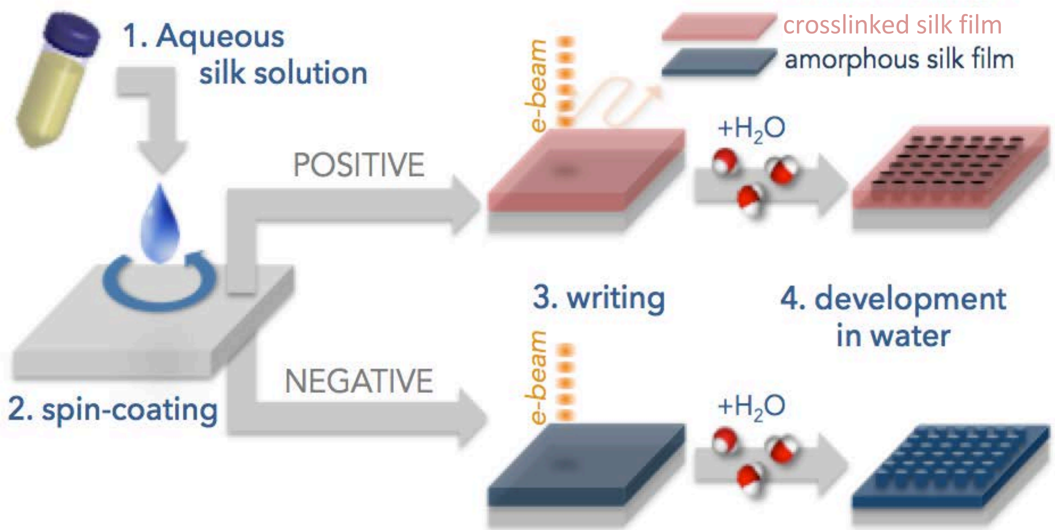
Nanofabrication of structural proteins can be achieved using top-down approaches as electron beam lithography

Engineering nanostructures:

i. Material final structure can be engineered with top-down strategies.

ii. The process can be achieved completely 'out of the hood' with water-based 'chemistry'

iii. Sub-10 nm resolution can be achieved both as positive or negative resist



Kim, Marelli et al, Nature Nanotech, 2014

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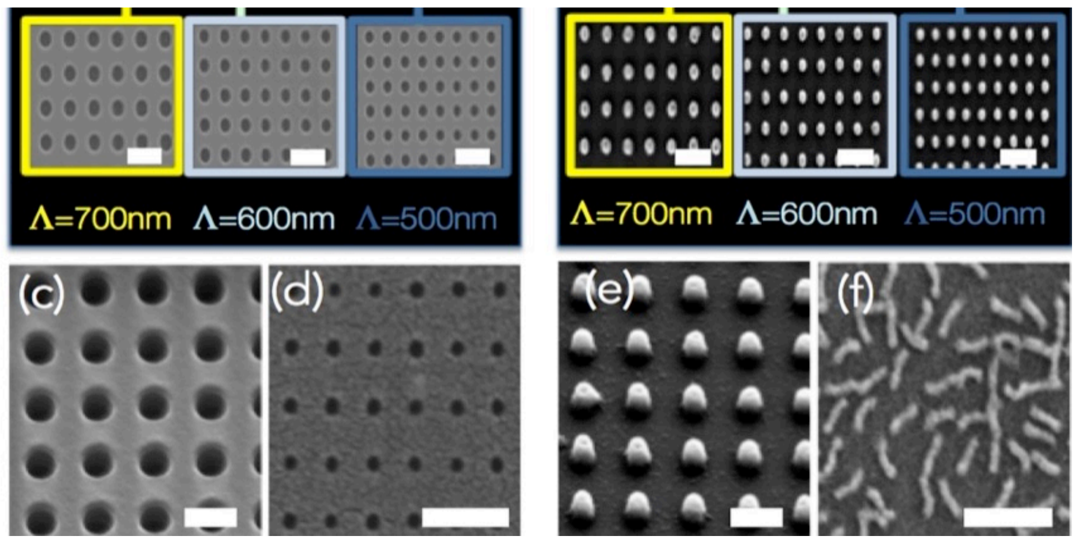


Kim, Marelli et al, Nature Nanotech, 2014

Biofabrication of structural proteins in advanced materials can be achieved by directing and templating self-assembly and by modulating polymorphism, bound water and molecular weight

Engineering structures:

i. The material final structure can be engineered with bottom-up approaches.

ii. Templating self-assembly allows to obtain complex shapes with no need for 'machining'

iii. Alternatively, simple biopolymers blocks (prism or cylindrically-shaped) may be fabricated and then machined to the final shape

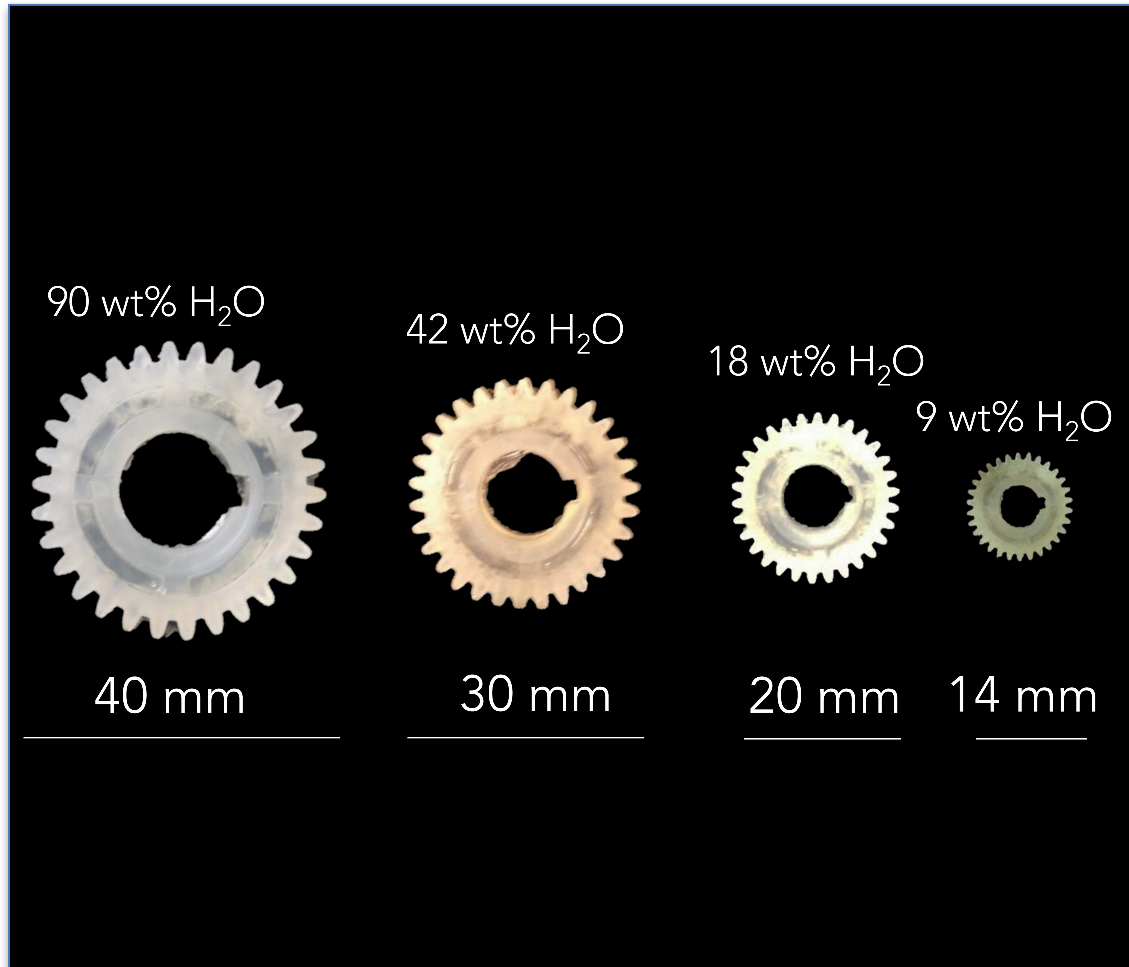
Marelli et al, PNAS, 2017

Biofabrication of structural proteins in advanced materials can be achieved by directing and templating self-assembly and by modulating polymorphism, bound water and molecular weight

Engineering structures:

Fabrication of three dimensional silk fibroin complex structures (e.g. gears) of defined dimensions by molding process.

Designing the original master has to take into account for shrinkage in the gel-solid processing step, due to evaporation of the mold.



Marelli et al, PNAS, 2017

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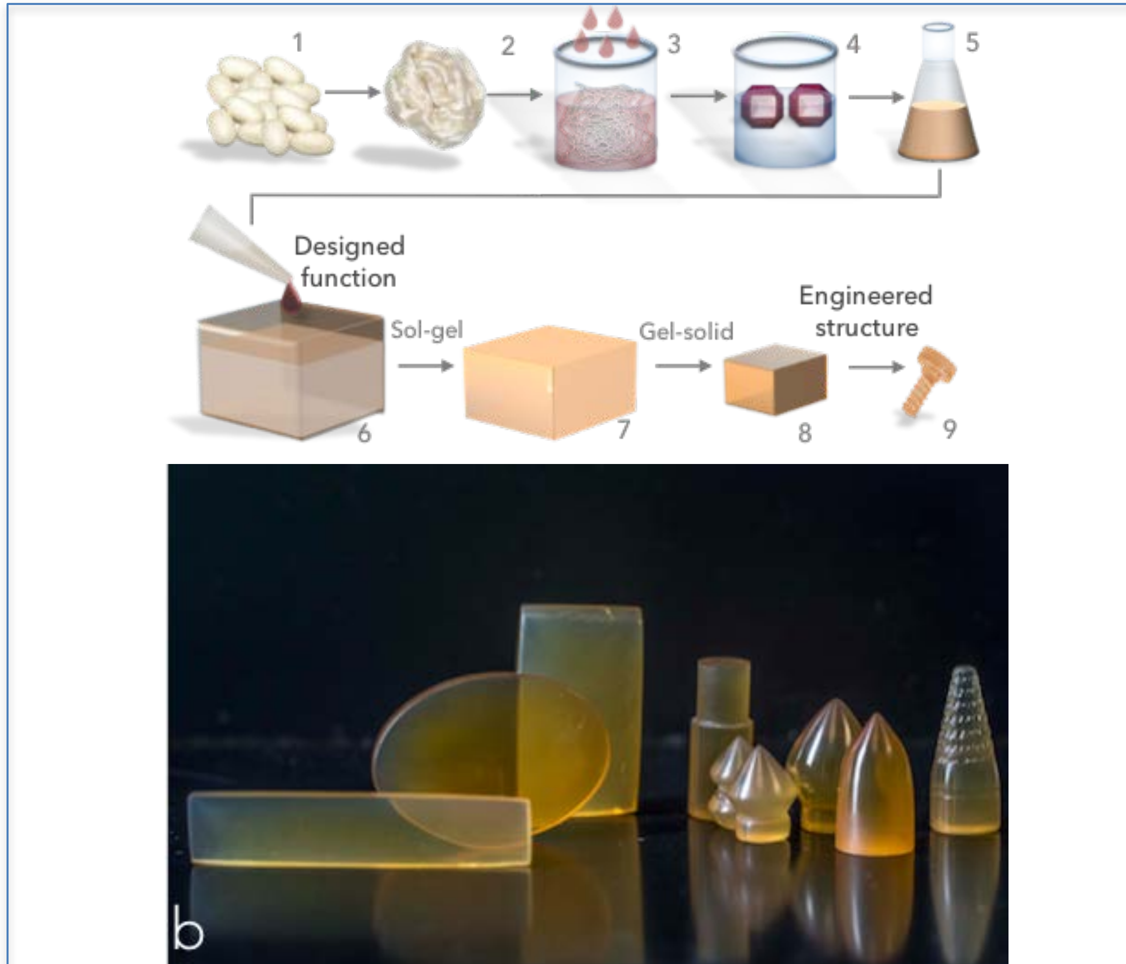
Unexpected functions can be achieved by doping biopolymer structures with water-soluble molecules that impart 'orthogonal' properties to the final material

Designed functions:

i. New functionalities may be achieved by fabricating 'hybrid materials' via doping at the point of material self-assembly



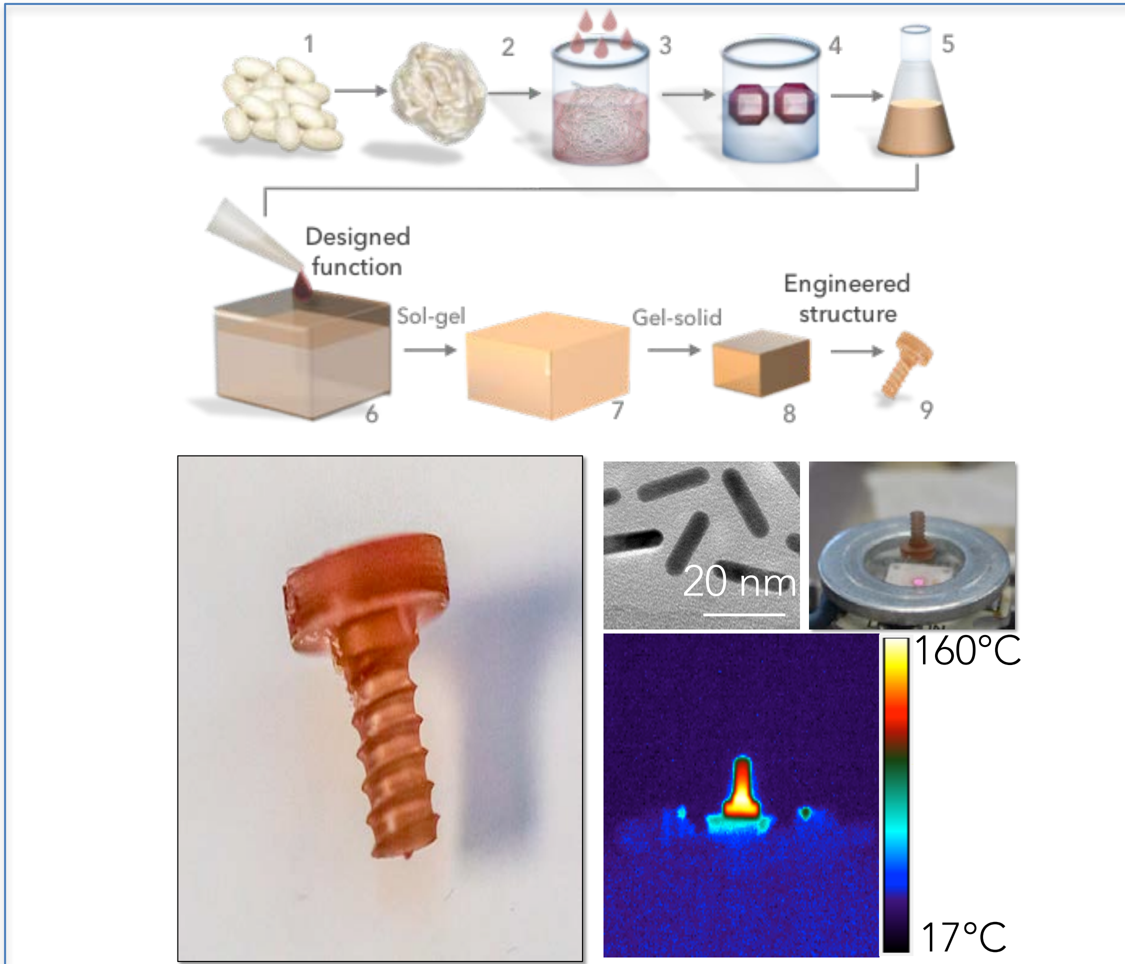
Marelli et al, PNAS, 2017

Unexpected functions can be achieved by doping biopolymer structures with water-soluble molecules that impart ‘orthogonal’ properties to the final material

Designed functions:

i. New functionalities may be achieved by fabricating ‘hybrid materials’ via doping at the point of material self-assembly

ii. Gold nanorods with tailorable plasmonic resonances may be incorporated, yielding mechanical components that heats up when irradiated with visible (red) and near-IR light.



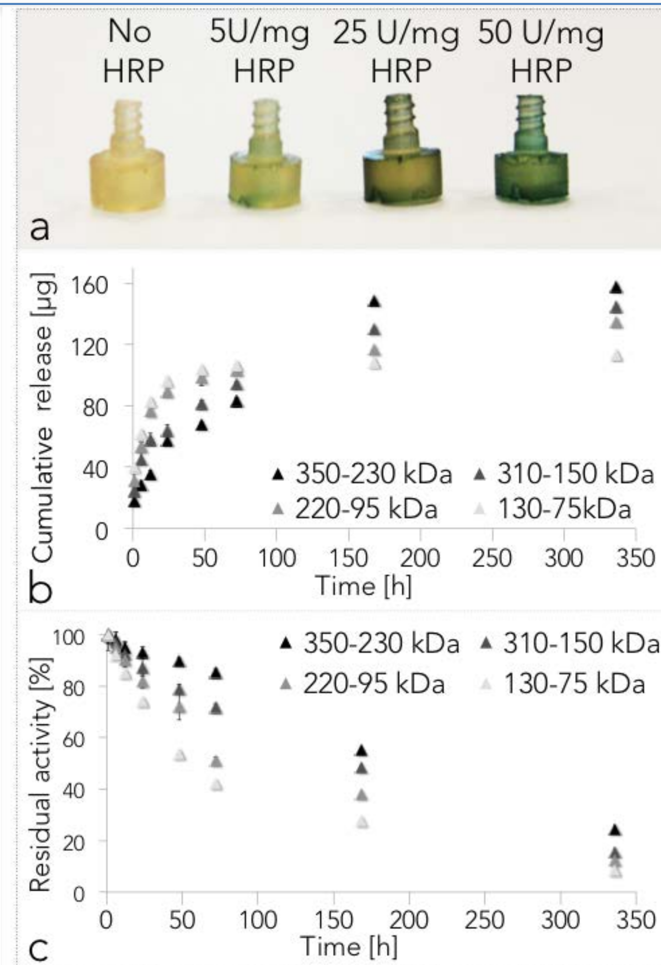
Marelli et al, PNAS, 2017

Unexpected functions can be achieved by doping biopolymer structures with water-soluble molecules that impart 'orthogonal' properties to the final material

Designed functions:

i. New functionalities may be achieved by fabricating 'hybrid materials' via doping at the point of material self-assembly

ii. Engineered silk fibroin screws with biological functions - horseradish peroxidase can be incorporated in engineered silk screws to impart catalytic activities to the material.



Marelli et al, PNAS, 2017

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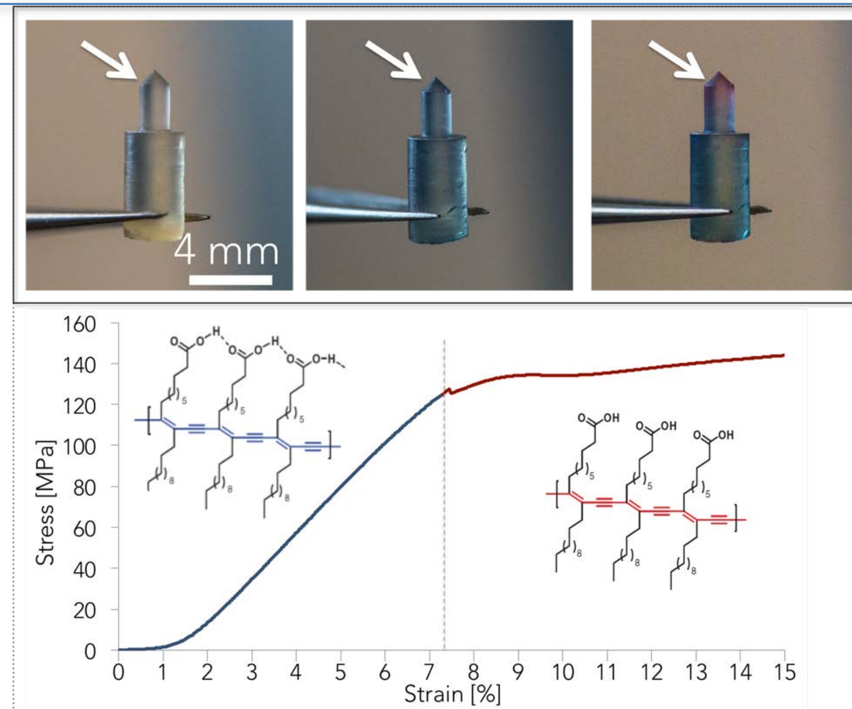
Unexpected functions can be achieved by doping biopolymer structures with water-soluble molecules that impart 'orthogonal' properties to the final material

Designed functions:

i. New functionalities may be achieved by fabricating 'hybrid materials' via doping at the point of material self-assembly

ii. Polymers that change in color when exposed to mechanical stresses may be incorporate to design mechanical components that 'sense' when they are plastically deformed (i.e. yield point)



Silk fibroin molecular weight	Strain-induced blue→red chromatic transition [%]
350-230 kDa	5.68±0.32
310-150 kDa	6.24±0.77
220-95 kDa	7.59±0.45
130-75 kDa	8.56±0.82

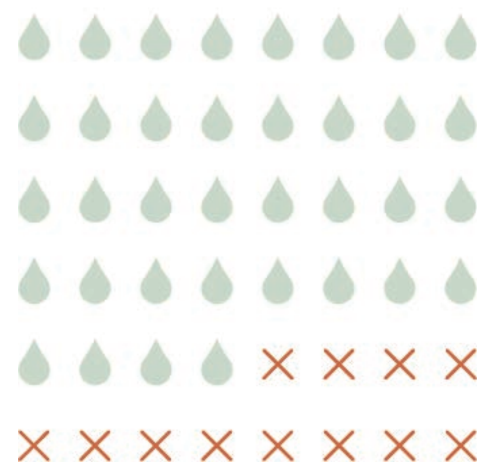
C

Marelli et al, PNAS, 2017

WIRED

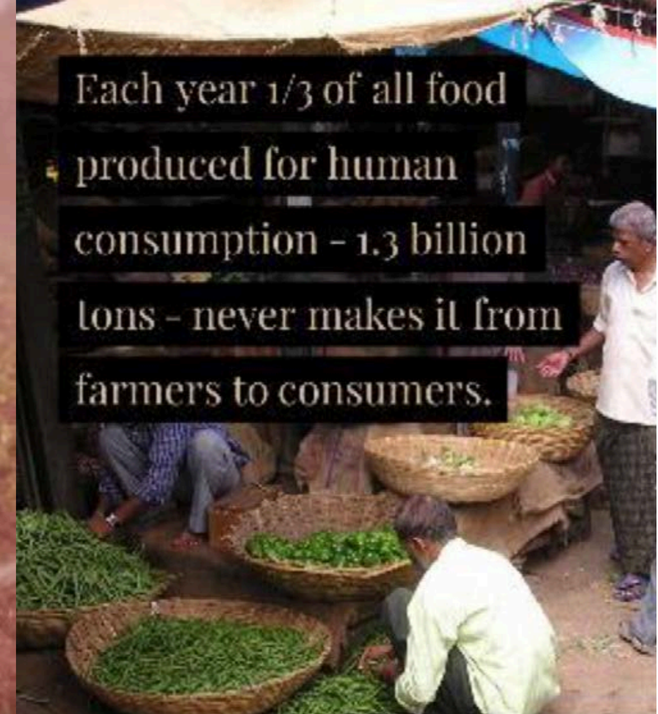
WITH 9B MOUTHS TO FEED BY 2050, WE HAVE TO GET BUSY NOW

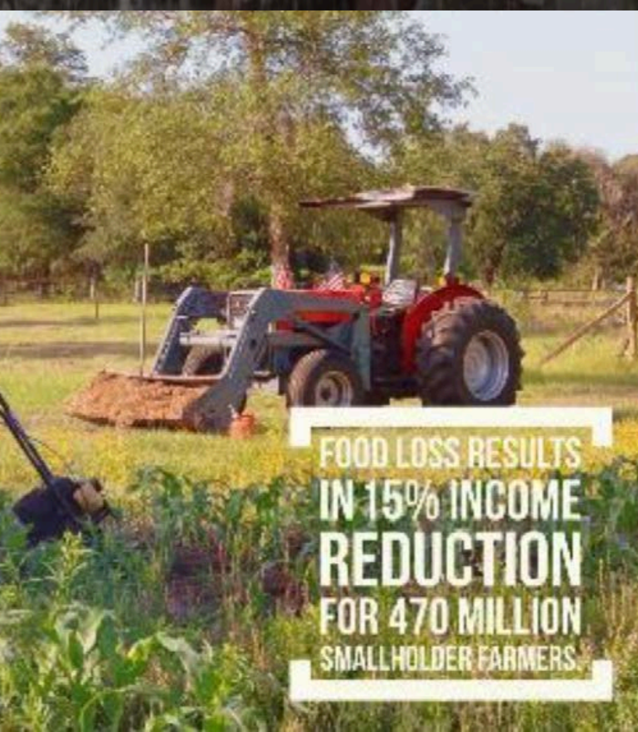
One quarter of global freshwater consumption is used producing food that is never eaten.




THE FOOD
LOST EVERY
YEAR COULD
FEED AN ESTIMATED
1.6 BILLION
PEOPLE GLOBALLY.


MORE THAN A
QUARTER
OF THE WORLD'S
FRESHWATER
& FIFTH OF ITS
FARMLAND
ARE USED TO
PRODUCE
FOOD THAT IS
NEVER
CONSUMED.


Each year 1/3 of all food
produced for human
consumption - 1.3 billion
tons - never makes it from
farmers to consumers.

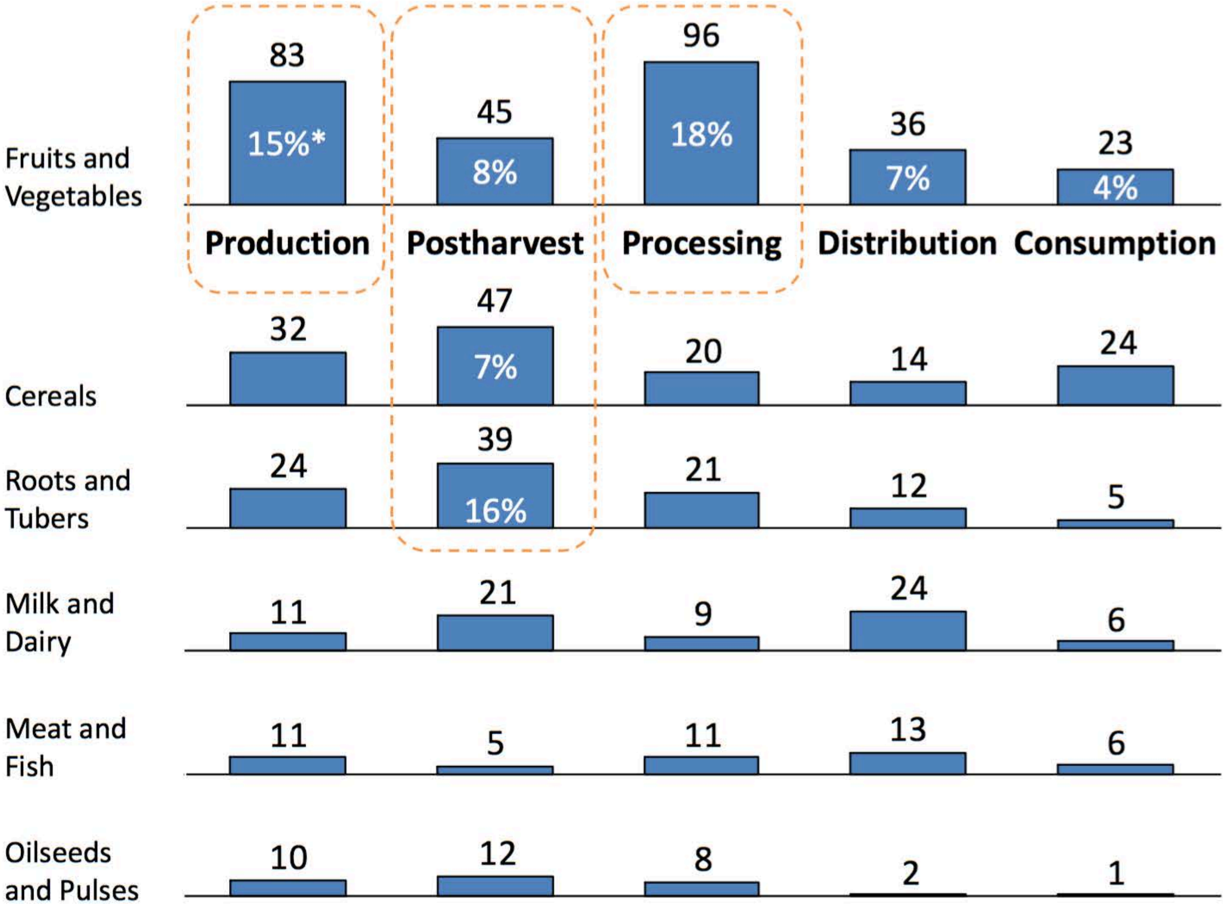

FOOD LOSS RESULTS
IN 15% INCOME
REDUCTION
FOR 470 MILLION
SMALLHOLDER FARMERS.


53 MILLION TONS
OF FOOD ARE
SENT TO LANDFILL
IN THE US EVERY
YEAR.


AMERICAN CONSUMERS,
BUSINESSES, AND FARMS
WASTE 40% OF
THE FOOD GROWN AND
PRODUCED FOR
CONSUMPTION
EVERY YEAR.

Amount of wastage in developing countries, millions of metric tons and as % of production[1]

The largest sources of loss in developing countries are in fruits and vegetables and the postharvest storage of cereals, roots, and tubers.



Primary Root Causes

Fruits and Vegetables:
- Production: 15%* is lost through manual harvest, bad weather during the harvest season, and premature harvest due to cash constraints.
- Postharvest: 8% is lost, mainly due to bruising or damage from improper packaging or handling, lack of cold storage in warm and humid climates, and seasonality that yields surpluses.
- Processing: 18% is lost due to high seasonality and poor storage, together lowering incentives to build processing capacity that meets total demand.

Cereals:
- Postharvest: 7% is lost due to improper storage, attributable to poor hygiene, pest infestation or bumper harvests beyond capacity.

Roots and Tubers:
- Postharvest: 16% is lost, mainly due to lack of cold storage in warm climates and distance to market.

*Note: Percentages listed are share of total category production in developing countries.

The Telegraph

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News

The end of the mouldy fruit bowl? Scientists discover microscopic silk covering to keep food fresh

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A Silky Solution to the Problem of Wasted Food?

By DANIEL AKST

May 19, 2016 2:27 p.m. ET

Food waste is a big problem, and produce is particularly vulnerable. Largely due to spoilage, 40-50% of the world's fruit and vegetable output is wasted, according to a U.N. estimate, along with a great deal of labor, water and energy.

Silk Fibroin as Edible Coating for Perishable Food Preservation

TIME

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This One Surprising Trick Might Keep Fruit Fresh for Longer

NEWSFEED

This One Surprising Trick Might Keep Fruit Fresh for Longer

Olivia B. Waxman @OBWax | May 6, 2016

CNN Tech » 6 wonders of science you didn't know were made from silk

The food preserver

Could silk be used to preserve our fruit in the future?

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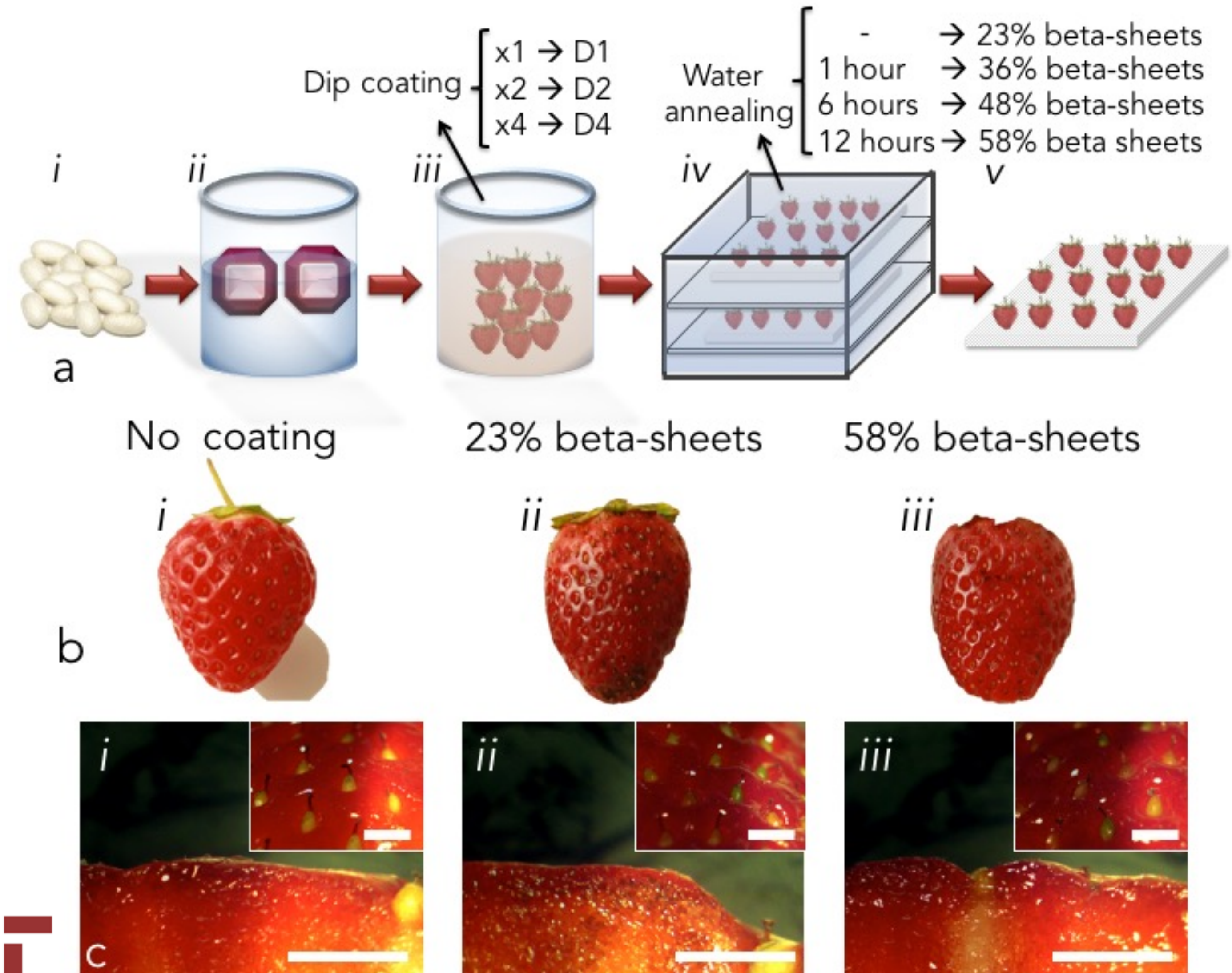
Edible coating for perishable food preservation



THE WALL STREET JOURNAL.

R AND D

A Silky Solution to the Problem of Wasted Food?

Tufts University researchers have developed an invisible coating that seems to protect fruits from deteriorating for days without refrigeration

Researchers at Tufts University have developed a solution made from silk that can coat produce and keep it fresh for a week without the need for a refrigerator. WSJ's

TIME SUBSCRIBE

NEWSFEED

This One Surprising Trick Might Keep Fruit Fresh for Longer

Olivia B. Waxman @OBWax SHARE

May 6, 2016

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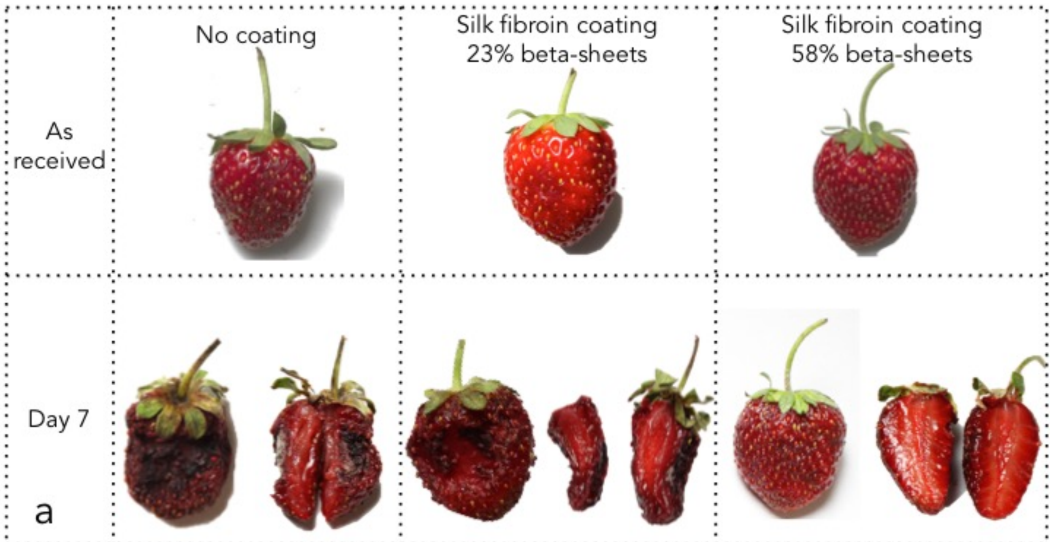
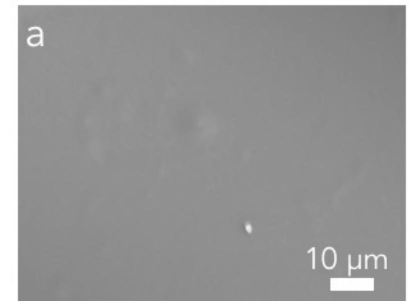
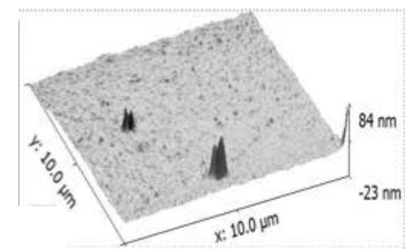
Getty Images

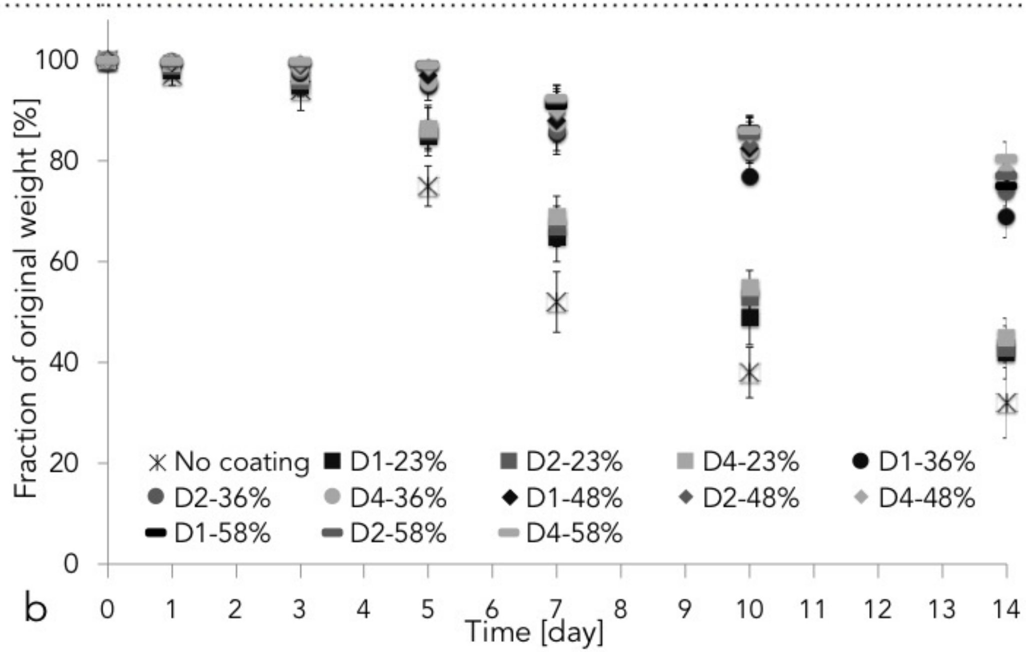
Marelli et al, Sci. Rep., 2016

Edible coating for perishable food preservation









Marelli et al, Sci. Rep., 2016

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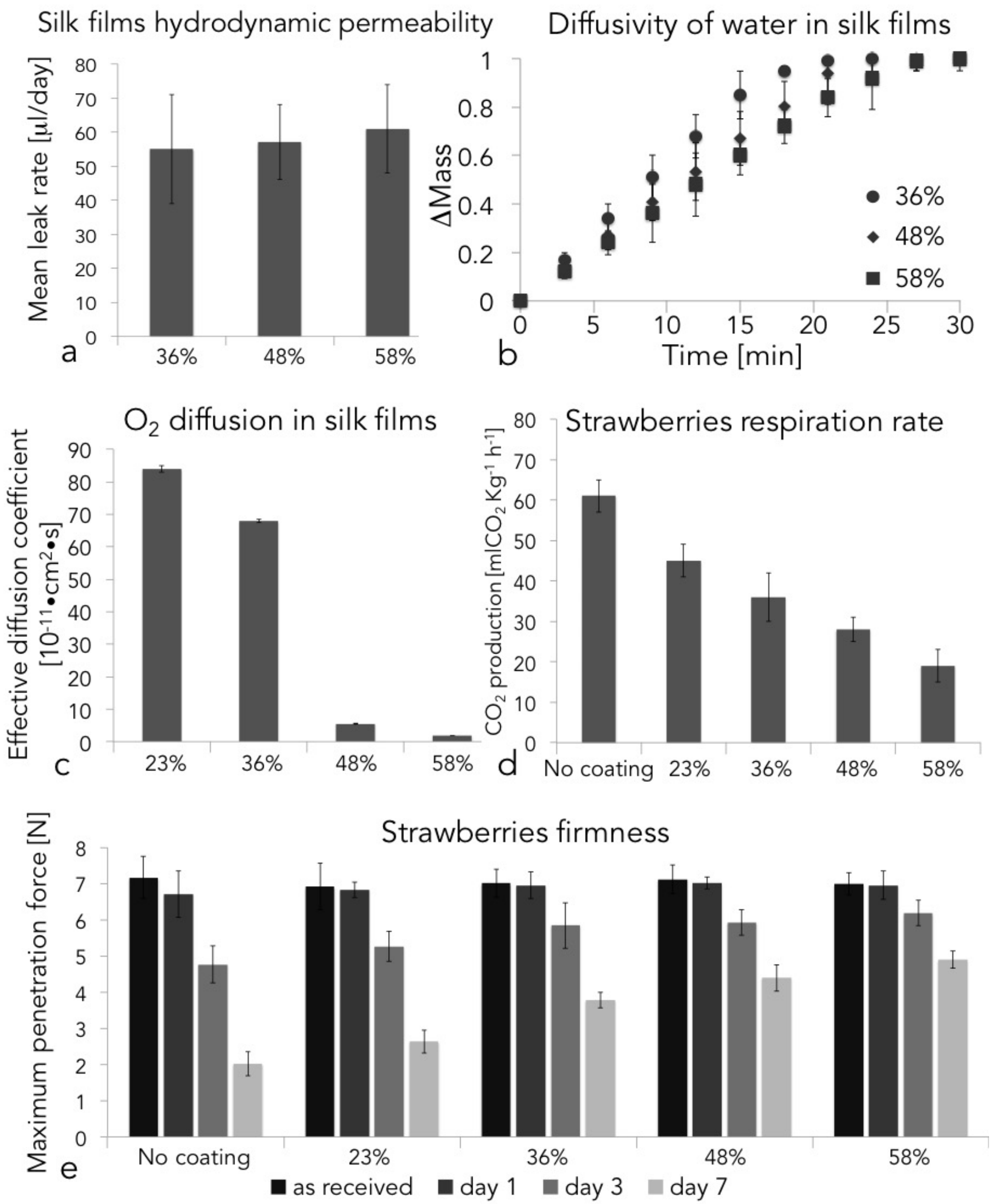
Edible coating for perishable food preservation



Marelli et al, Sci. Rep., 2016

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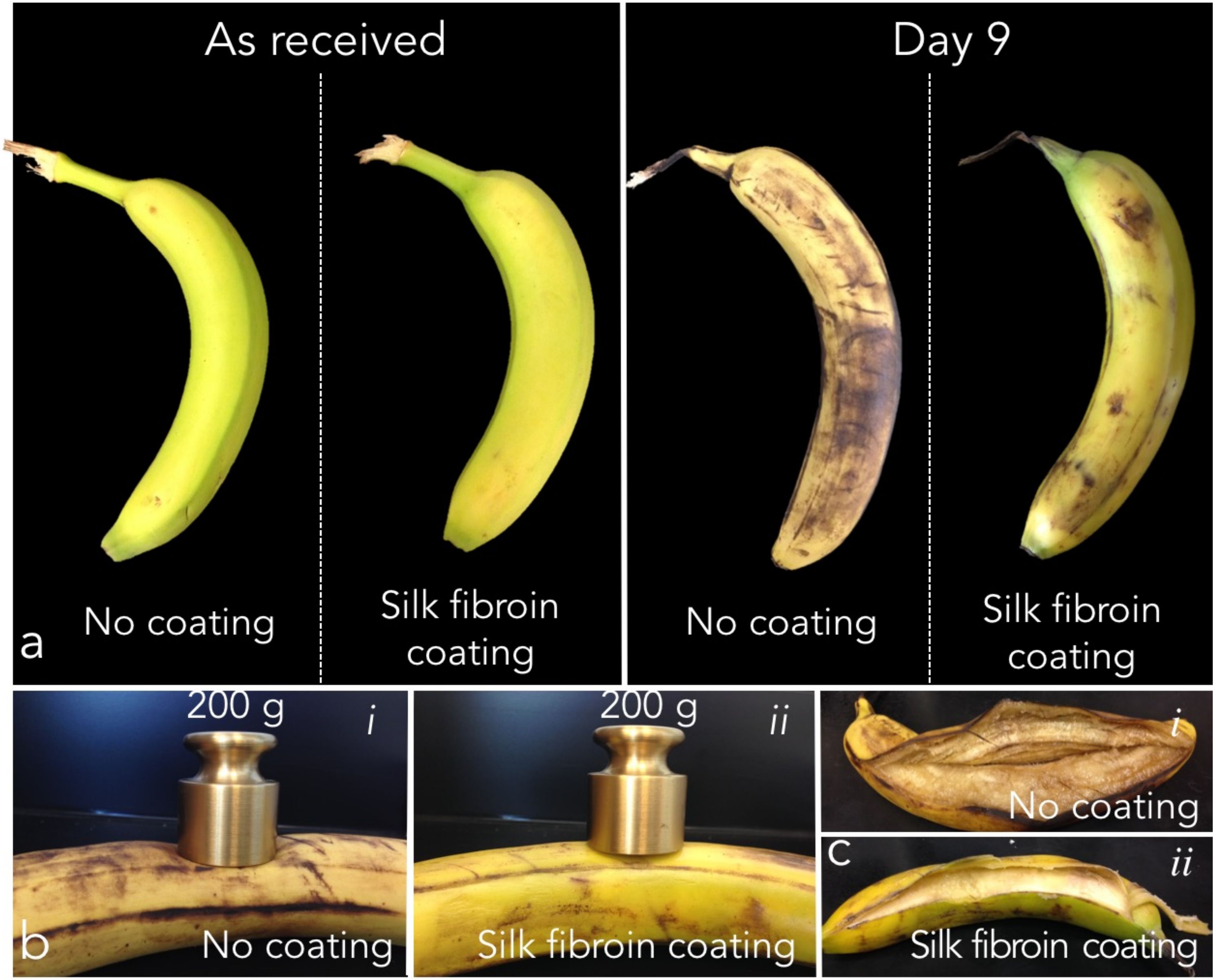
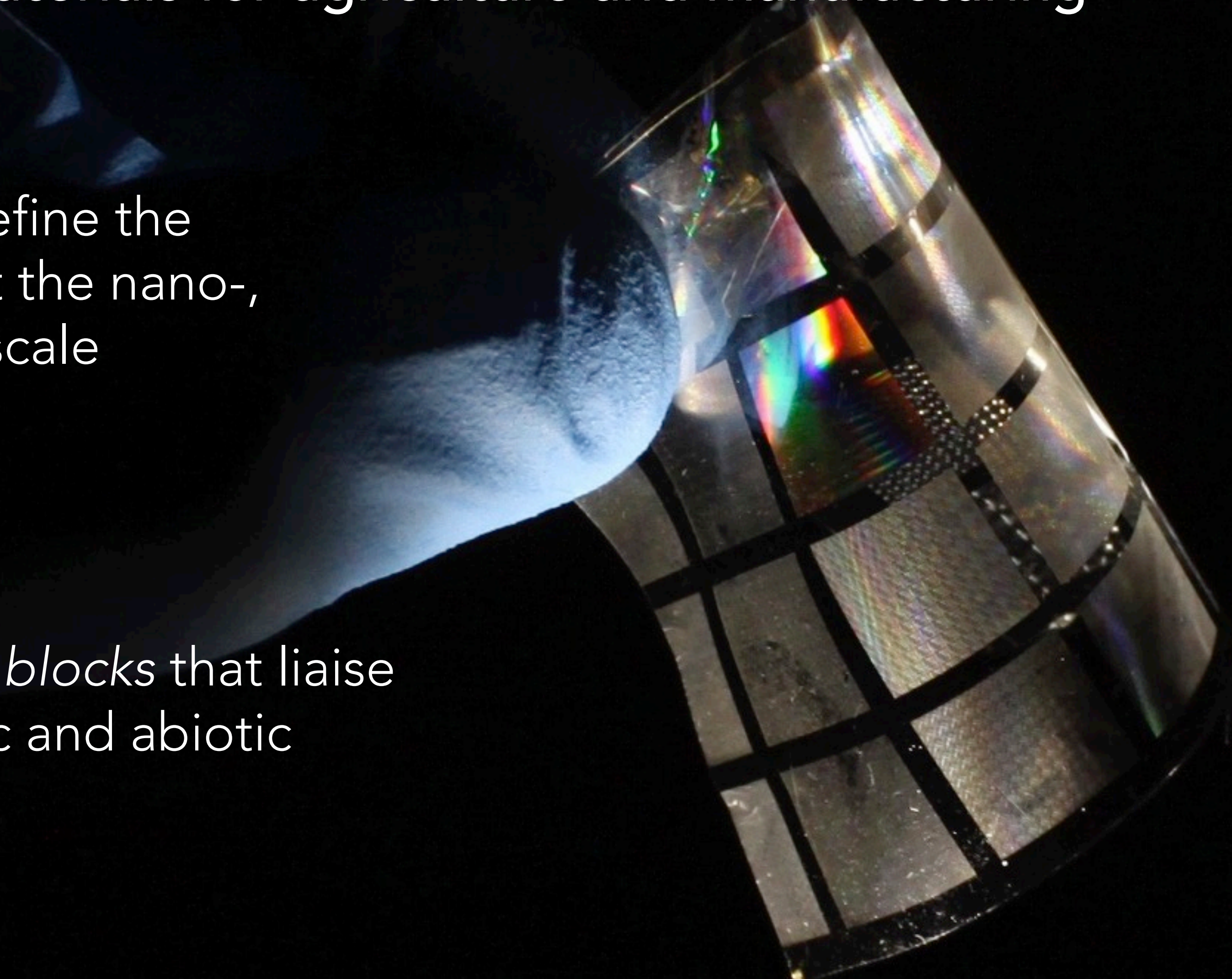


Structural biopolymers provide an unprecedented tool to address the technological thirst for innovative solutions in advanced materials for agriculture and manufacturing



New *bricks* to redefine the fabrication rules at the nano-, meso- and micro-scale

Universal *building blocks* that liaise between the biotic and abiotic worlds

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Structural Biopolymers: using Nature's building blocks as an inspiration for advanced manufacturing

Benedetto Marelli, Laboratory for Advanced Biopolymers, CEE @ MIT

Biomaterials tomorrow

bio-instructive
respond to their surroundings
transform themselves
disappear harmlessly
biocompatible without sacrificing technological performance
have "non-obvious" functions

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