Transient Robotics: Foundations and Applications

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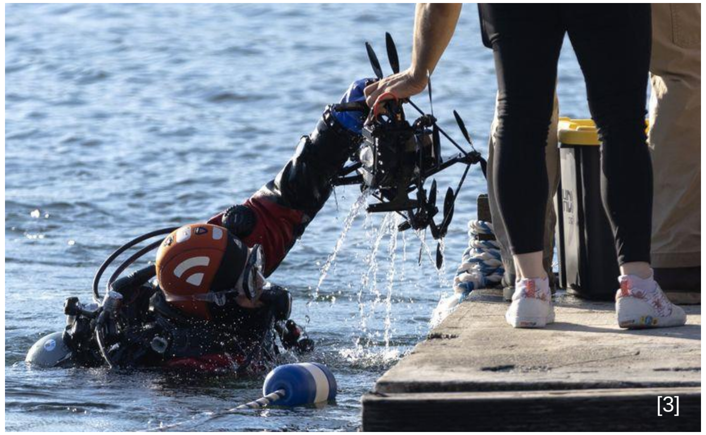
Introduction – Lecture goals

- Purpose:
  - Aims to explore the materials, design, and real-world application of biodegradable robots
- Topics:
  - Understand the need for biodegradable robots
  - Explore biodegradable materials and their integration into robotics
  - Highlight key design challenges and solutions

Motivation – Environmental Challenges

- Problem: Robots left in ecosystems pose contamination risks
- Risks to sensitive ecosystems



Source: [1] https://www.heliguy.com/blogs/posts/drone-crashes-top-5-causes/; [2] https://x.com/AerialEducator/status/915645698409947148;
[3] https://www.seattletimes.com/seattle-news/48-of-55-drones-at-fourth-of-july-seatac-fail-recovered-at-angle-lake/

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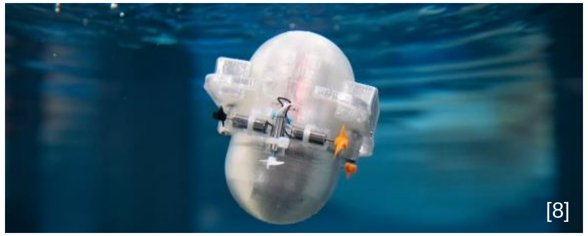
Motivation – Biodegradability in Robotics

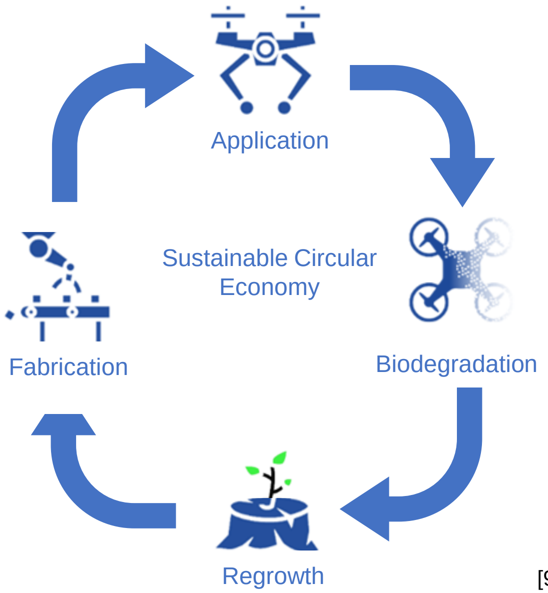
- Transient robots:
  - *“Transient robots are a class of environmental sensing robots, which are made from biodegradable and bio-resorbable materials. To comply with the circular economy design paradigm, the materials used shall be not petroleum based and shall biodegrade under natural conditions within a maximum of one year.”*

Manual sensor deployment

Robotic assistance



Transient robotics following circular economy



[9]

Source: [4] Figueiredo et al., IEEE IFIP, Paris, 2009.; [5] Fraunhofer IMS, press-release, 2011.; [6] E. Aucone, et al., Sci. Rob., 2023.; [7] Miki, et al., *Sci. Rob.*, 2023.; [8] Gunnarson, et al., *Nat. Com.*, 2021.; [9] Wiesemüller, et al., *IEEE AIRPHARO*, 2021.

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Motivation – Transient Robotics

transient 1 of 2 *adjective*

tran·sient ˈtran(t)-sh(ē-)ənt ˈtran-zē-ənt, ˈtran(t)-sē-; ˈtran-zhənt, -jənt

Synonyms of *transient* >

1 **a** : passing especially quickly into and out of existence : TRANSITORY

transient beauty

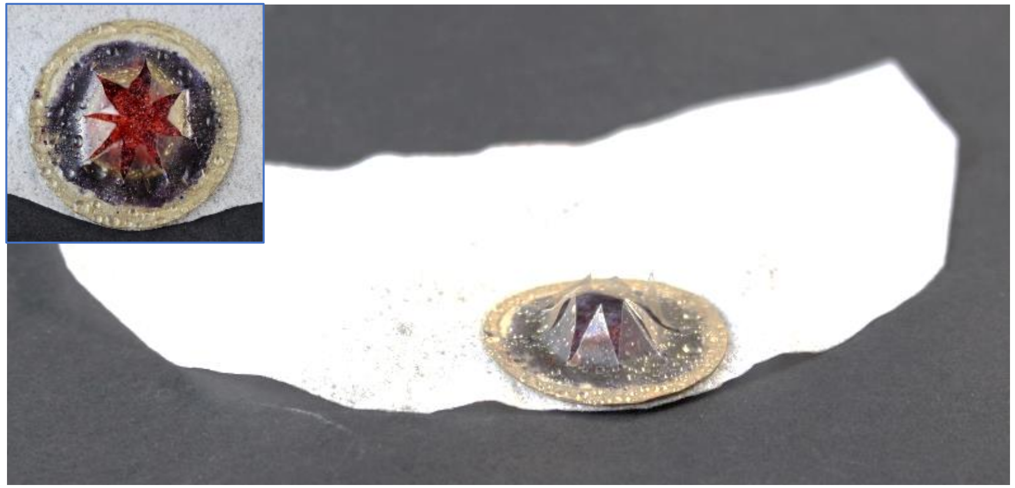
b : passing through or by a place with only a brief stay or sojourn

transient visitors

2 : affecting something or producing results beyond itself

transiently *adverb*

Motivation – Areas of Application I



- **Environmental Monitoring:**
  - **Transient Drones:**
    - Deployable drones made of biodegradable materials for collecting data in sensitive ecosystems.
    - Example: Monitoring forest health or water pollution without leaving waste behind.
  - **Biodegradable Sensors:**
    - Sensors for pH, humidity, or temperature monitoring in ecosystems.
    - Decompose harmlessly after their purpose is served.
  - **Wildlife Tracking Devices:**
    - Temporary, eco-friendly tracking devices for studying animal migration and behavior without long-term environmental impact.

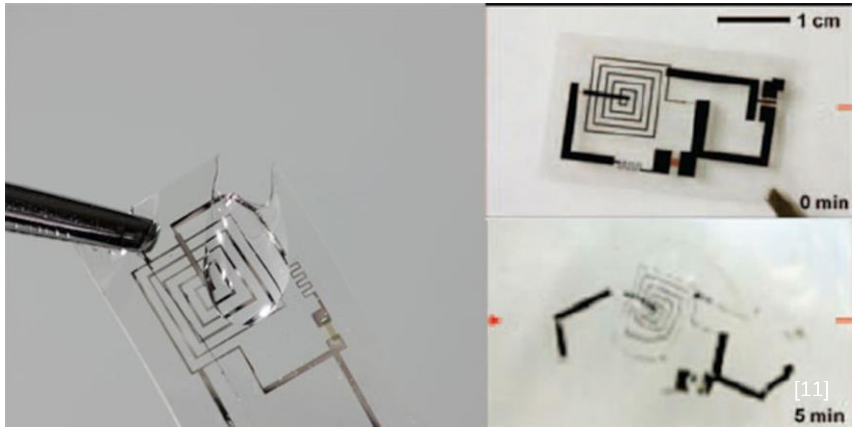
Motivation – Areas of Application II

- **Agricultural Applications**
  - **Soil Health Monitoring:**
    - Biodegradable robots and sensors for analyzing soil quality and detecting contaminants.
  - **Seed-Planting Robots:**
    - Autonomous biodegradable robots for precise planting, reducing machinery-induced soil compaction.
  - **Crop Monitoring and Pest Control:**
    - Biodegradable robots for monitoring crop health, pest activity, and optimizing pesticide or fertilizer use.

Source: [10] URL: https://www.3dnatives.com/en/4d-printed-robot-seed-analyzes-conditions-010520236/.

Motivation – Areas of Application III

- **Biomedical Applications**
  - **Temporary Implants:**
    - Biodegradable surgical devices and implants that dissolve after healing, eliminating the need for removal surgeries.
    - Examples: Biodegradable stents, sutures, and drug delivery systems.
  - **Tissue Engineering:**
    - Biodegradable scaffolds for supporting cell growth and regeneration.
    - Promotes sustainable and non-invasive medical practices.
  - **Transitory Biosensors:**
    - Biodegradable sensors for monitoring vital signs, designed to dissolve after short-term use.



Source: [11] URL: https://www.nationalgeographic.com/science/article/dissolving-electronics-medical-sensors-that-disintegrate-after-a-fixed-time.

Motivation – Broader Impact

- Impact of transient robotics in various fields
  - Reduced physical interaction (e.g. noise, human presence)
- Sustainability as a design philosophy
  - Co-development of robots and their bodies using only biodegradable materials
  - Reducing the environmental impact of environmental sensing campaigns, while keeping the environmental impact at minimum

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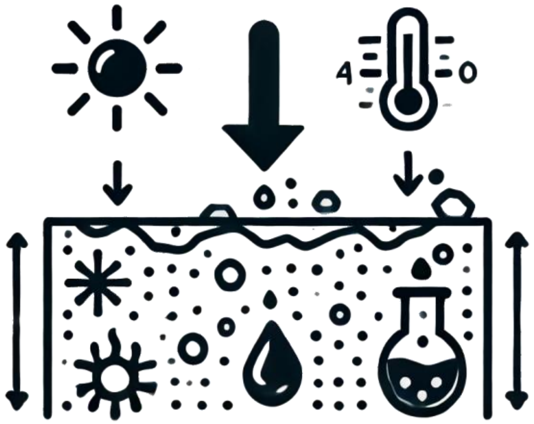
Biodegradable Materials – Basics

Biodeterioration

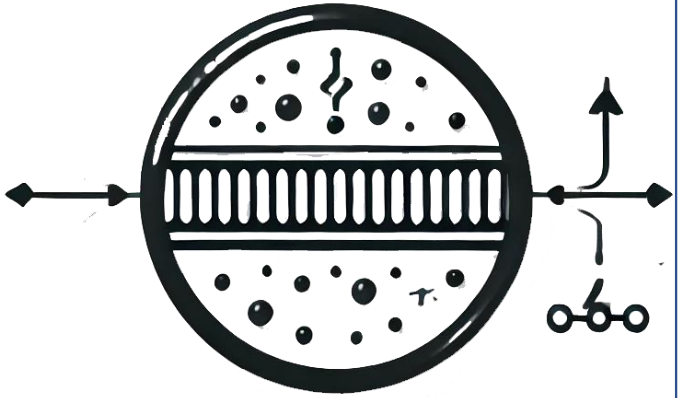


- Surface-level degradation
- Modification of mechanical, physical and chemical properties
- Abiotic factors enable further degradation by weakening the material

Biofragmentation

- Bonds within the polymer are destroyed
- Oligomers/monomers are generated
- Can be either aerobic (with O_2) or anaerobic digestion (without O_2)

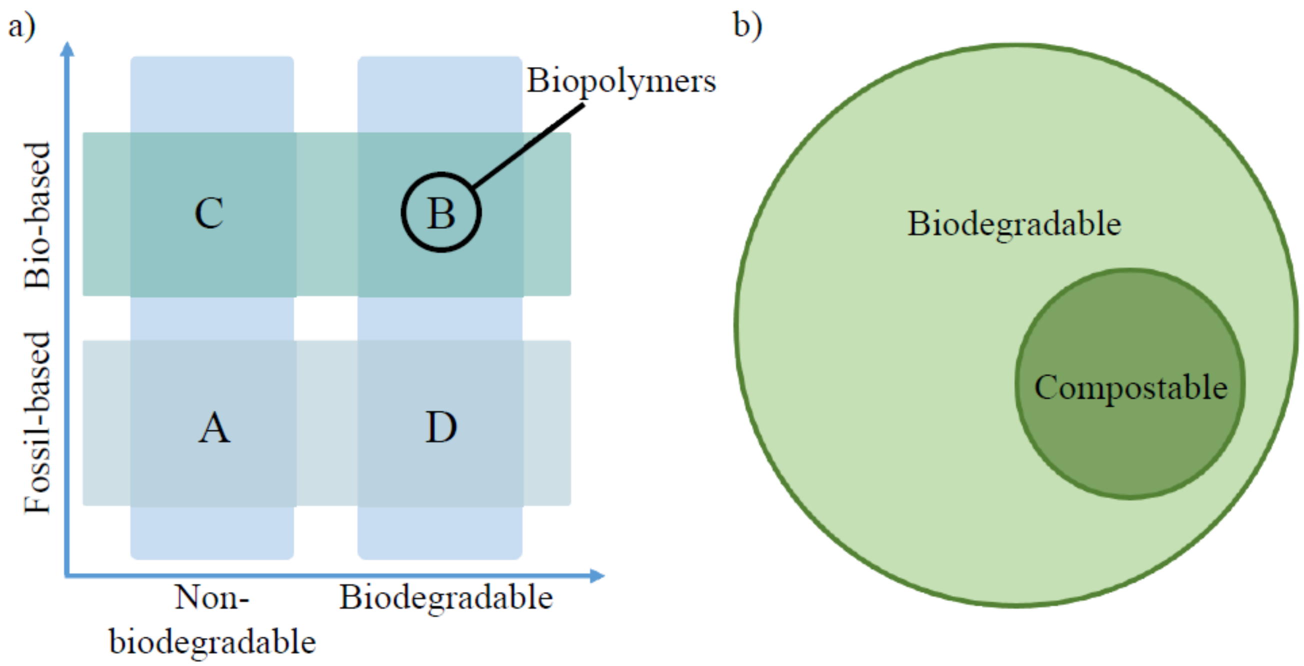
Assimilation



- Products of bio-fragmentation are integrated in microbial cells
- Catabolic pathways result in adenosine triphosphate (ATP) or cell structure elements

Biodegradable Materials – Types

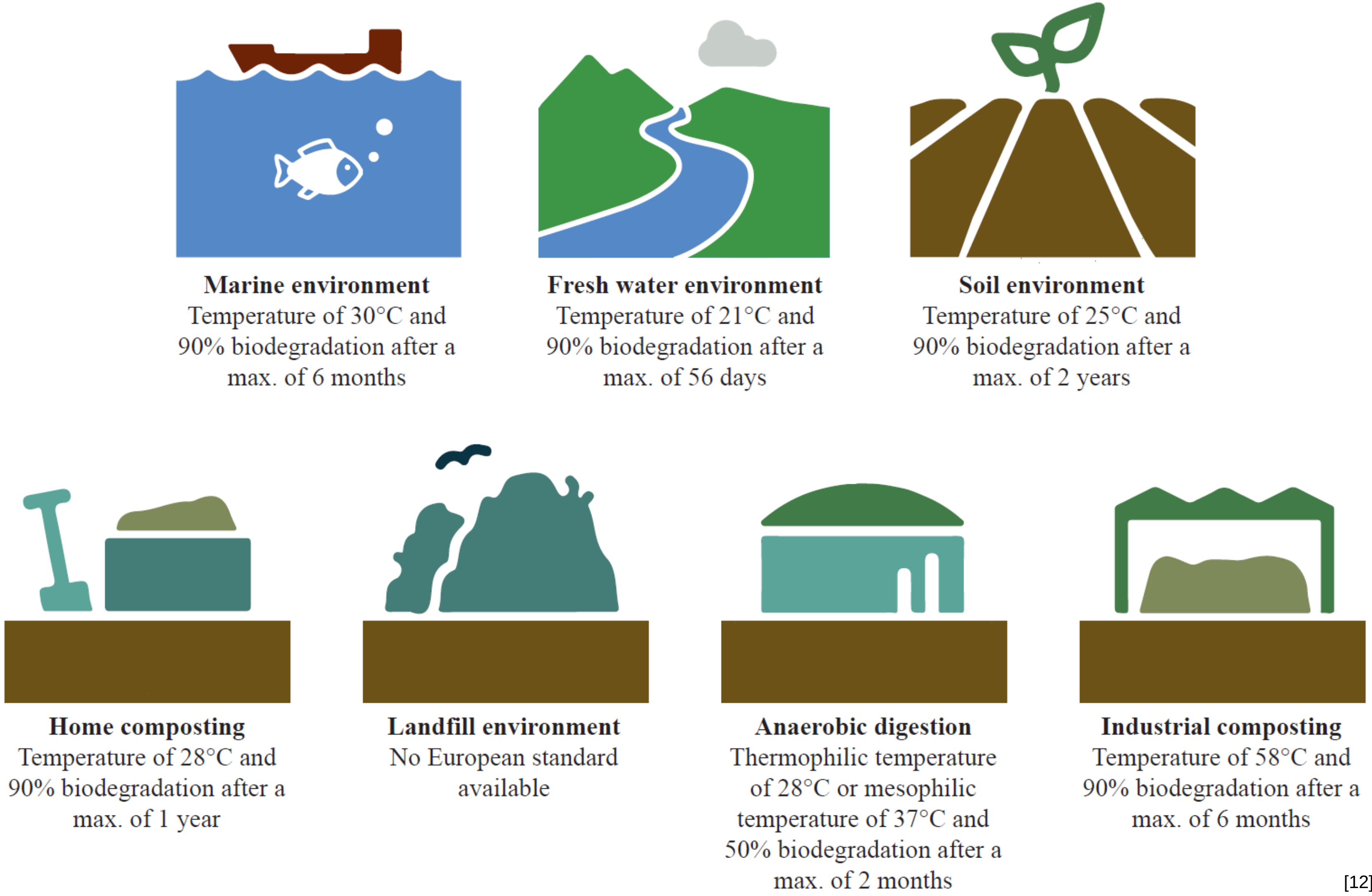
- Material requirements for the fabrication of transient robots
  - Bio-based
  - Compostable in its deployment environment



Biodegradable Materials – Certification I

- Biodegrada-bility depending on respective environment

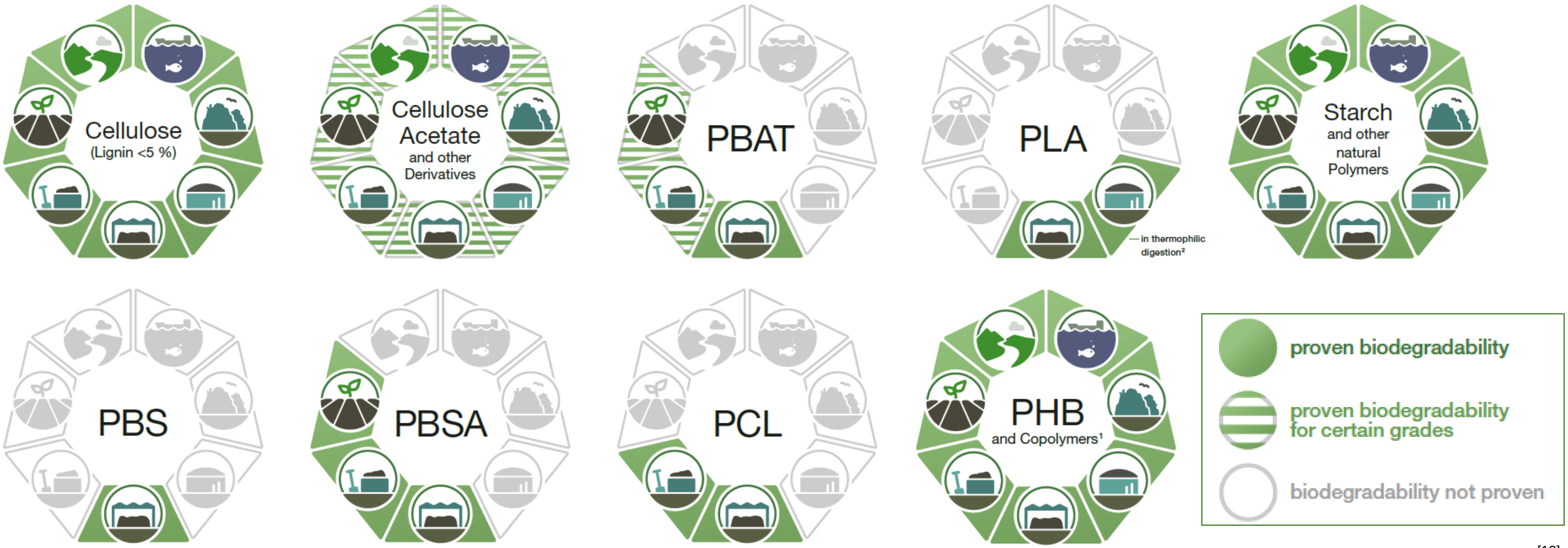
- Various standards available for marine, soil or composting



[12]

Source: [12] https://renewable-carbon.eu/publications/product/biodegradable-polymers-in-various-environments-%E2%88%92-graphic-pdf/, accessed: 09.12.2024.

Biodegradable Materials – Certification II

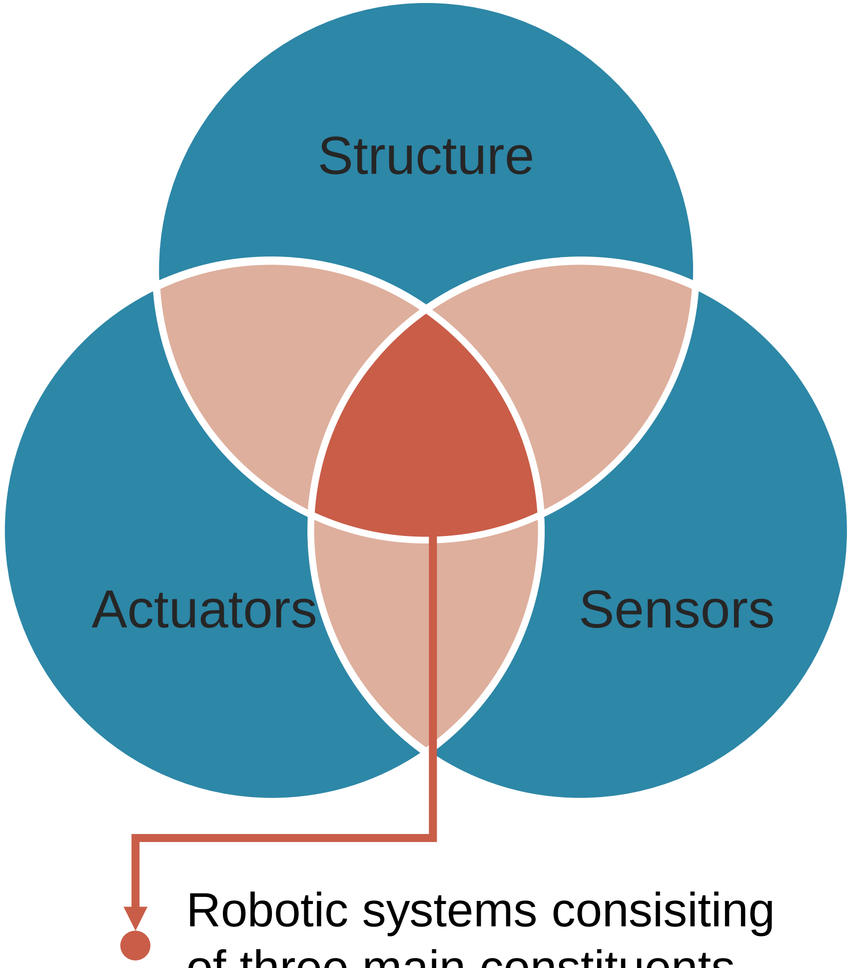


[13]

- Only cellulose, starch and Polyhydroxybutyrate (PHB) and its co-polymers are biodegradable in all environments

Source: [13] https://renewable-carbon.eu/publications/product/biodegradable-polymers-in-various-environments-%E2%88%92-graphic-pdf/, accessed: 09.12.2024.

Research example – Airframe Study



Robotic systems consisiting of three main constituents

Source: [14] F. Wiesemüller, et al., Adv. Int. Sys., 2023

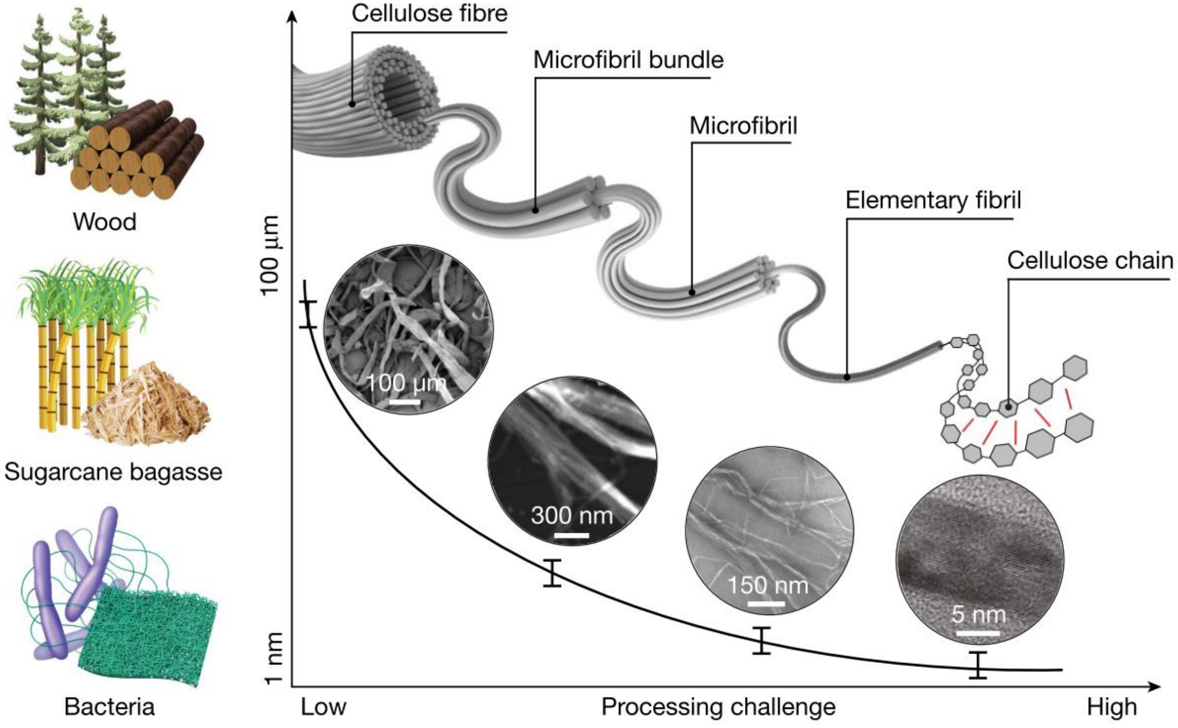
Biodegradable structures

Empa | Imperial College London

Image: Empa/SAM Architects/Filippo Bolognese

Structural materials – Cellulose

- Cellulose = the most abundant polymer on earth
  - High mechanical properties
  - Compostable & sustainable
  - Negative CO_2 footprint



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Source: [15] ???

Current applications


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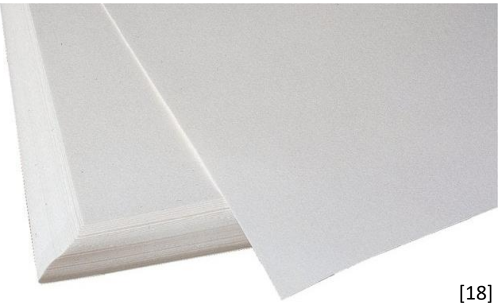
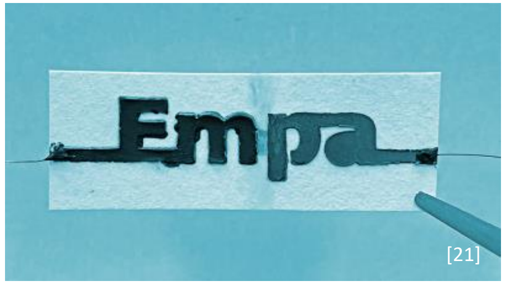

[18]

Future applications


[19]

[20]



[21]

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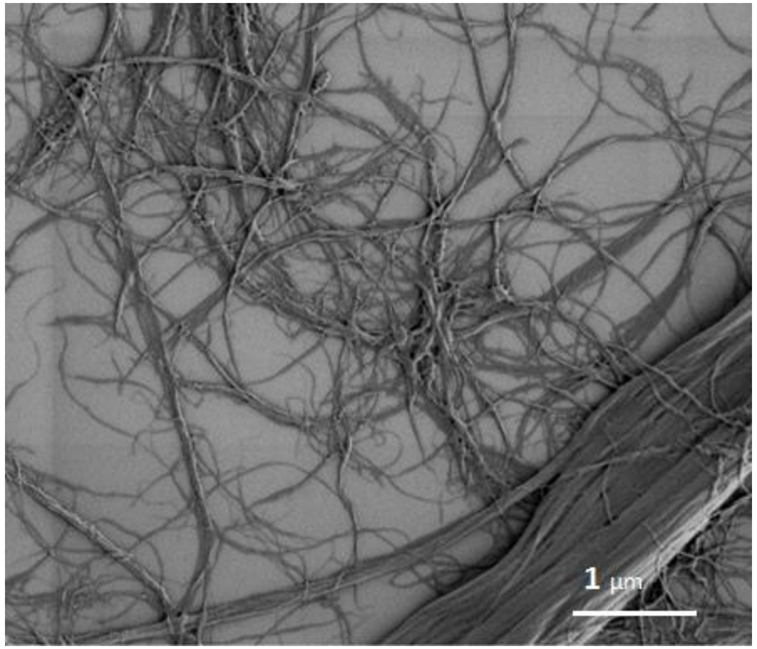
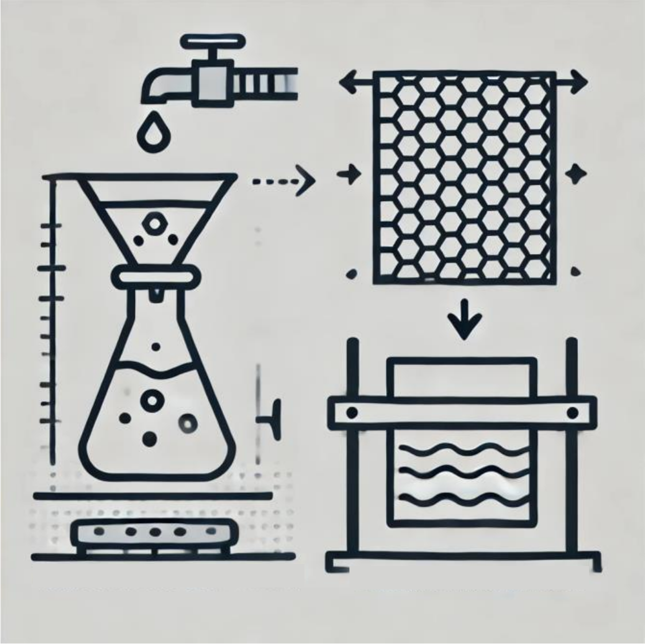
Images: Creativity103, Fisher Scientific

Structural materials – Cellulose 2D

- **Nanocellulose Suspensions and Filtration-Based Approaches**
- Microfiltration of Cellulose Nanofibrils (CNF) or Microfibrillated Cellulose (MFC)
  - Vacuum filtration of a dilute cellulose nanofibril suspension onto a membrane
  - Formation of a uniform hydrogel “cake” that can be pressed and dried to yield a dense cellulose nanopaper/film





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Source: [XXMFC] URL: https://www.wetend.com/more-with-less-trumpjet-flash-mixing-system-for-mfc-and-nfc/; [XXSEM] URL: https://blog.borregaard.com/exilva/how-to-characterize-microfibrillated-cellulose-reliably

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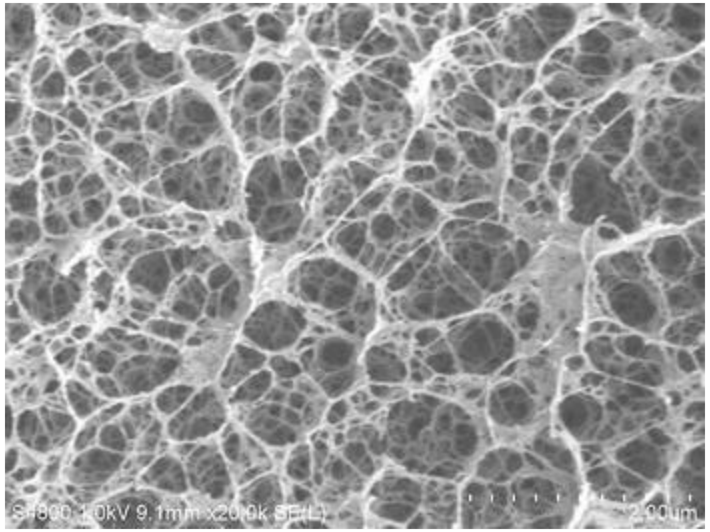
Structural materials – Cellulose 2D

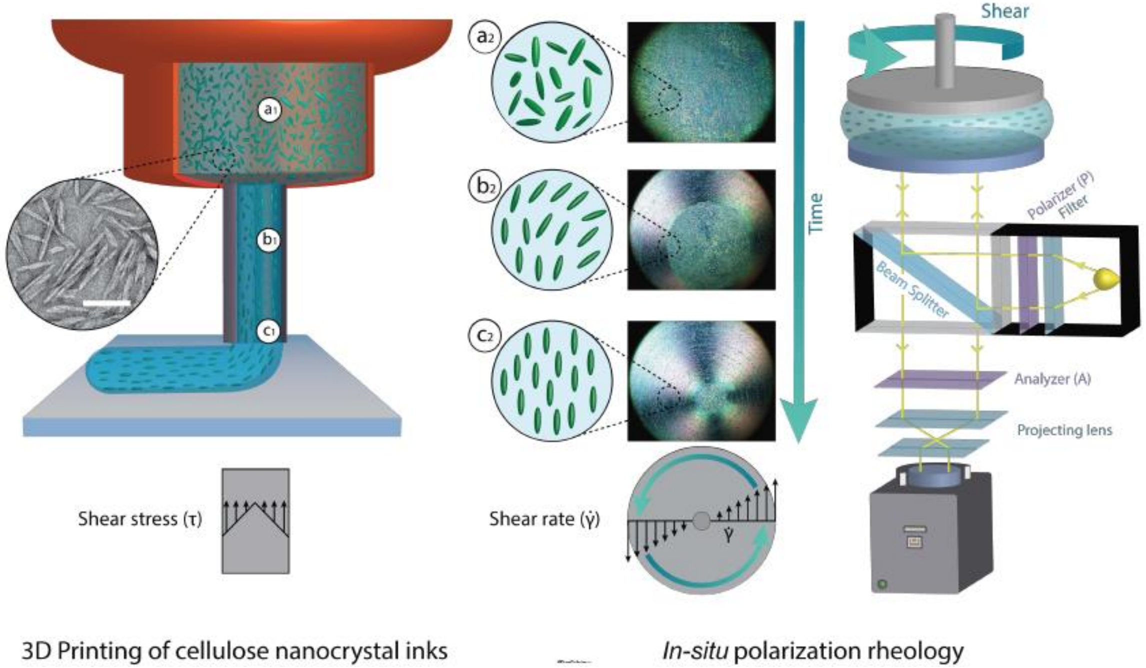
- **Drying Techniques for Film Consolidation**
- Ambient Air Drying
  - Allowing filtered or cast cellulose gels to dry at room temperature, resulting in films with relatively high porosity
    and some shrinkage
- Controlled Humidity Drying
  - Drying under regulated humidity conditions to minimize deformation and cracks
- Hot-Press Drying
  - Applying heat and pressure simultaneously to densify the film and reduce drying time
- Freeze-Drying (Lyophilization)
  - Freezing the cellulose gel and sublimating the ice under vacuum, producing highly porous structures
    (more common for aerogels, can be compressed into films)

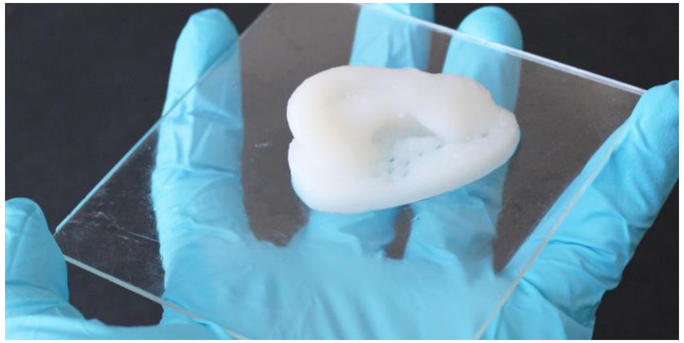


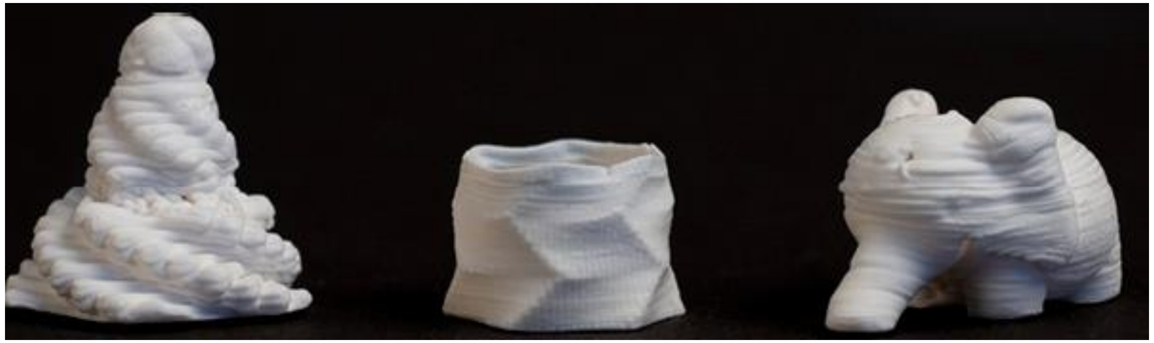
Source:URL: https://www.researchgate.net/figure/SEM-image-of-the-surface-morphology-of-the-regenerated-cellulose-film-after-being_fig2_322849809?__cf_chl_tk=0RwYckoIzzdBPRVmjUSqGmH8kIvUwlZidg5g3nb0mDU-1734037258-1.0.1.1-nOzRX88GU2tRX1d7SXaaMuMKq6T_SvQIC8W0t4ubLLA

Structural materials – Cellulose 3D

- **3D printing**
- Direct Ink Writing (DIW) / Robocasting of CNF Suspensions
  - Formulating a shear-thinning CNF-based hydrogel ink
  - Extruding the ink through a nozzle under controlled flow and depositing it layer-by-layer to create 3D structures.
- Fused Filament Fabrication (FFF) with Cellulose-Containing Filaments
  - Incorporating cellulose fibers, nanocellulose, or cellulose derivatives (e.g., cellulose acetate) into thermoplastic filaments
  - Printing via standard FFF printers to yield cellulose-reinforced or cellulose-based composites







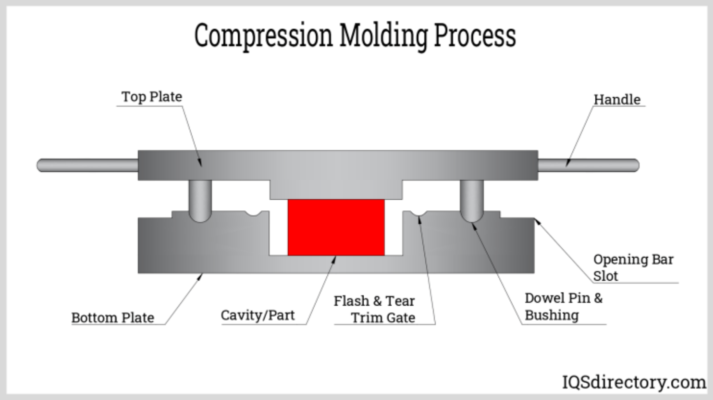
Source: [XXOhr] URL: https://ethz.ch/en/news-and-events/eth-news/news/2020/03/printing-complex-cellulose-based-objects.html; [Xxbaum+vase] URL: https://www.empa.ch/web/s604/3d-printed-cellulose-aerogel;

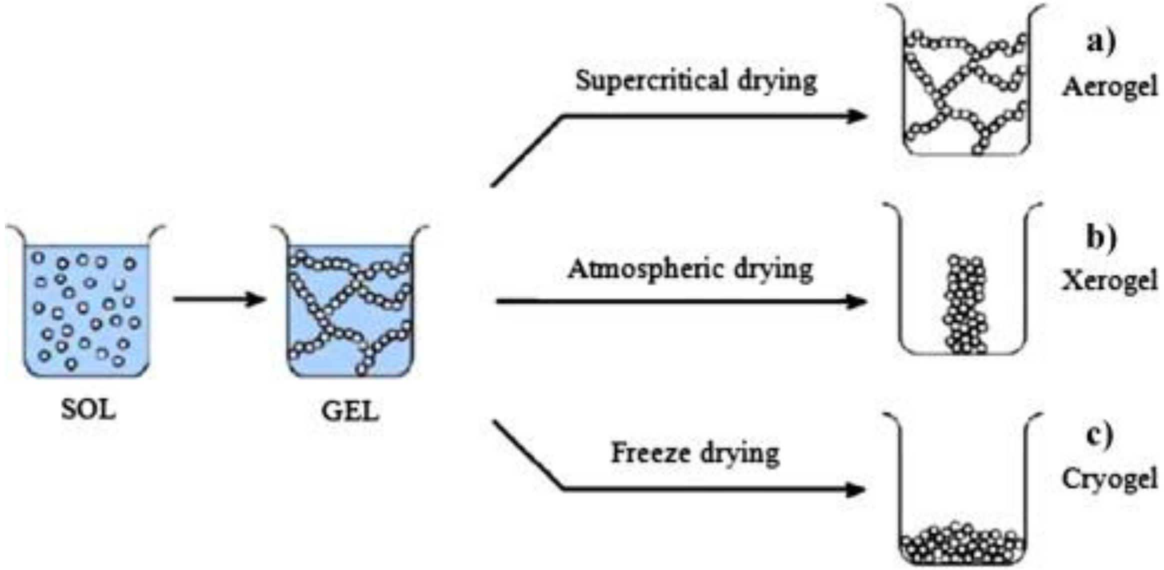
Structural materials – Cellulose 3D

- **Molding**
- Compression Molding and Hot-Pressing of Cellulose Composites:
  - Mixing cellulose fibers or nanocellulose with binding agents (e.g. lignin) or thermoplastics to form composite granules or mats
  - Applying heat and pressure in a mold to compress these materials into dense, shaped parts

- Freeze-Casting (Ice-Templating) of Cellulose Suspensions:
  - Freezing a cellulose nanofibril suspension, causing ice crystals to form a template
  - Sublimation of ice (freeze-drying) leaves behind a porous, anisotropic structure

- Supercritical Drying and Aerogel Formation:
  - Gelation of cellulose or nanocellulose in a solvent (often water or an ionic liquid), followed by solvent exchange and supercritical CO_2 drying.
  - This yields lightweight, porous aerogels that can be shaped using molds prior to drying.





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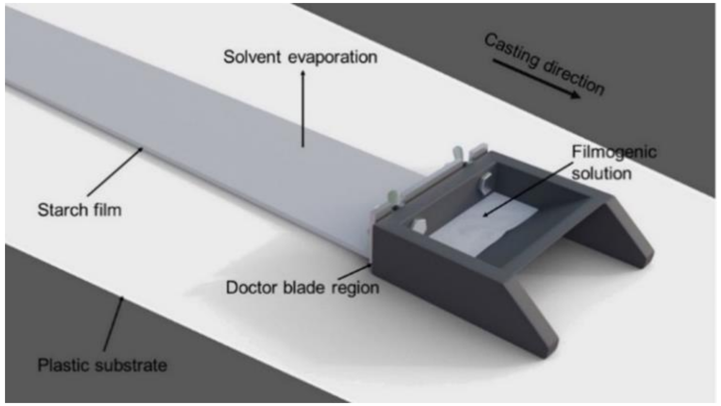
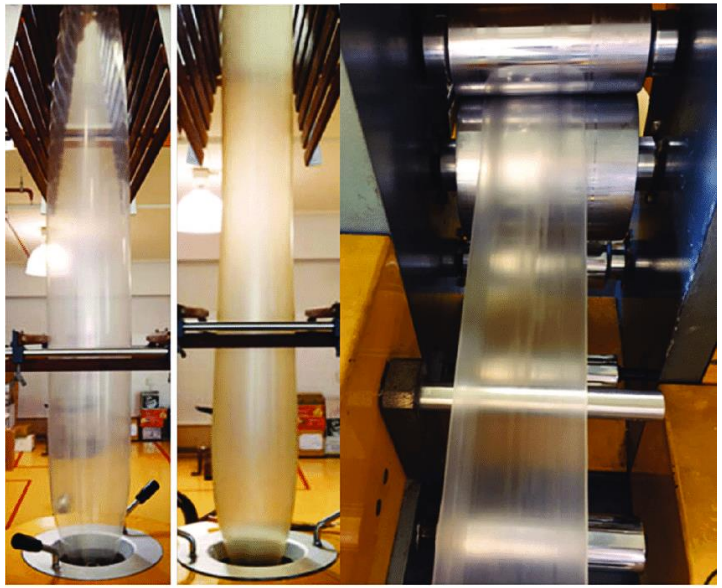
Source: [XXthomas] URL: https://www.empa.ch/web/s604/bioelektronik; [Xxmold] URL: https://www.iqsdirectory.com/articles/rubber-molding/compression-molding.html; [xxdrying] URL: https://www.sciencedirect.com/science/article/pii/S0896844612000757

Structural materials – Starch 2D

- Solution Casting (Solvent Casting)
  - Dissolving or suspending starch in water (often with plasticizers like glycerol or sorbitol) and heating
    to form a gelatinized solution.
  - Pouring the hot, viscous solution onto a flat surface (e.g., a Petri dish or Teflon plate).
  - Allowing it to dry at controlled temperature and humidity, resulting in a thin, flexible starch film

- Thermoplastic Starch (TPS) Film Extrusion
  - Mixing native starch with plasticizers under heat and shear conditions to produce thermoplastic starch
  - Using film extrusion techniques (e.g., blown film extrusion) to create continuous rolls of TPS-based films
  - This method is industrially scalable, producing films with varying thickness and properties





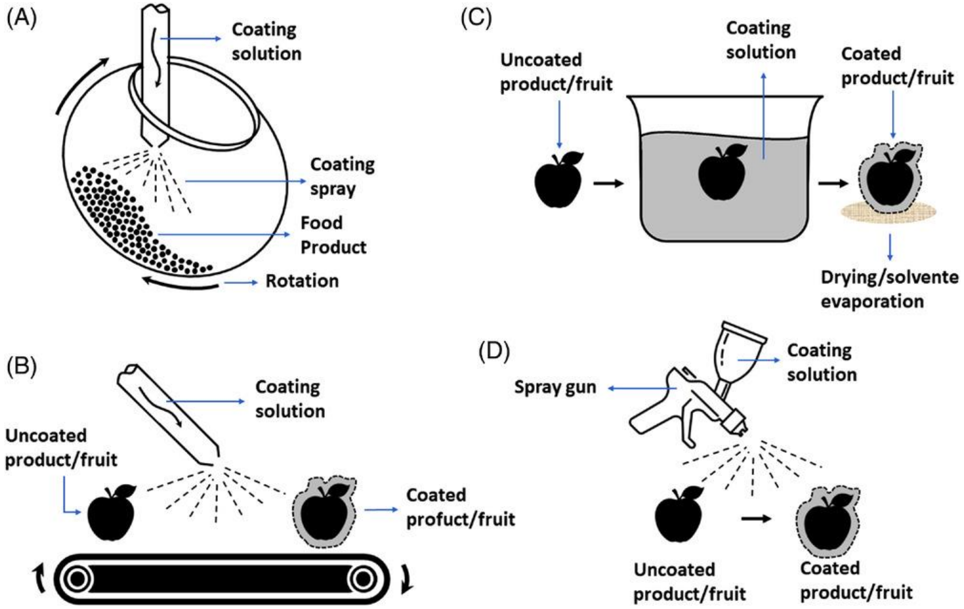
(A) (B)

Source: [xxstarch] URL: https://blog.potatoworld.eu/an-introduction-to-potato-starch-production ; [Xxblow extrusion] URL: https://www.researchgate.net/figure/Bioplastic-processing-via-A-blown-extrusion-of-starch-left-and-starch-protein-blends_fig4_350220845; [blade] URL: https://www.scielo.br/j/po/a/ZZrZMwyM3FB6KXryk5vR9sf/

Structural materials – Starch 2D

- Compression Molding of Starch Films
  - Preparing a starch-plasticizer mixture and placing it into a heated mold
  - Applying heat and pressure to form a uniform film as the starch gelatinizes and consolidates
  - Cooling the molded film under pressure to achieve the desired thickness and mechanical properties

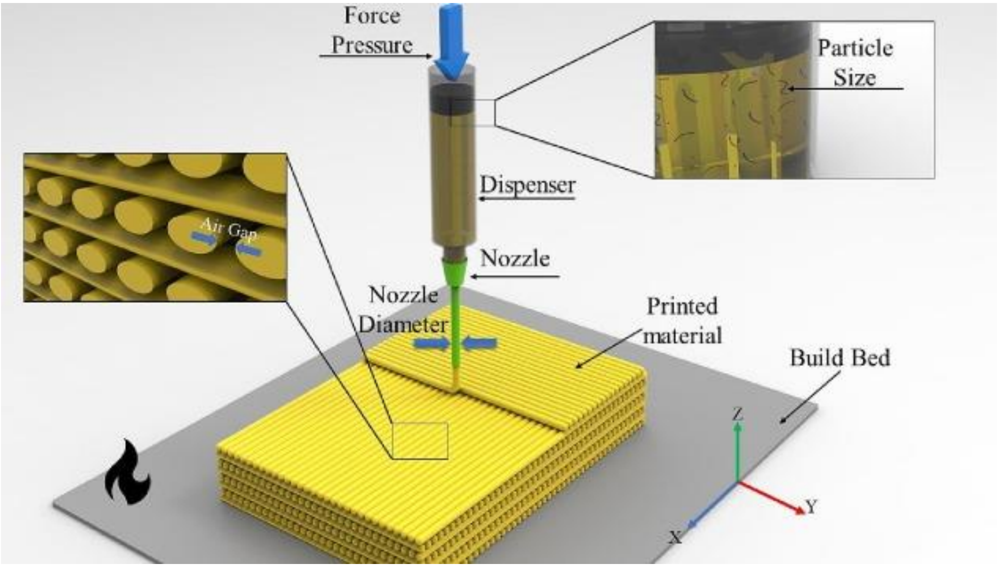
- Coating and Laminating
  - Using starch-based coatings on paper or polymer substrates
  - Applying a starch solution via rod coating, spraying, or dip coating and then drying
  - Producing thin starch layers or bilayer films by laminating starch films with other biodegradable polymers

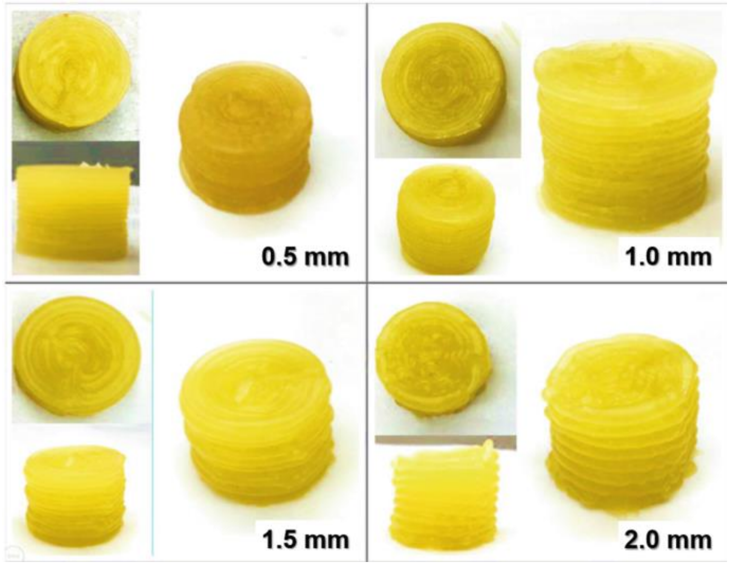


Source: [xxhotpress] URL: https://www.researchgate.net/figure/Schematic-illustration-of-compression-molding-process_fig1_317040762; [xxcoat] URL: https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100279

Structural materials – Starch 3D

- **3D printing**
- Direct Ink Writing of Starch Pastes
  - Formulating a starch-based paste or hydrogel ink with an appropriate rheology.
  - Extruding the paste through a nozzle layer-by-layer using a 3D printer to build up structures (e.g., customized food products, biodegradable tissue engineering scaffolds)
  - Post-processing (e.g., drying, crosslinking) to enhance mechanical stability

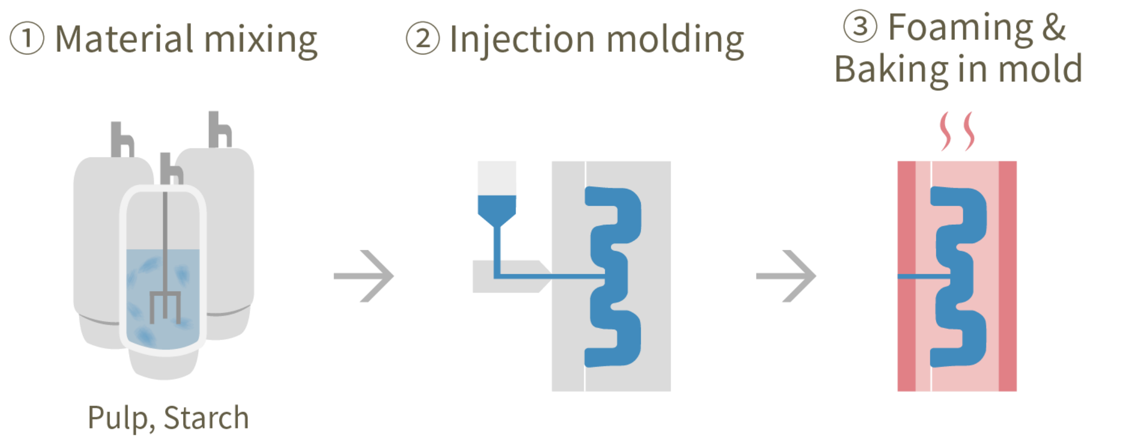


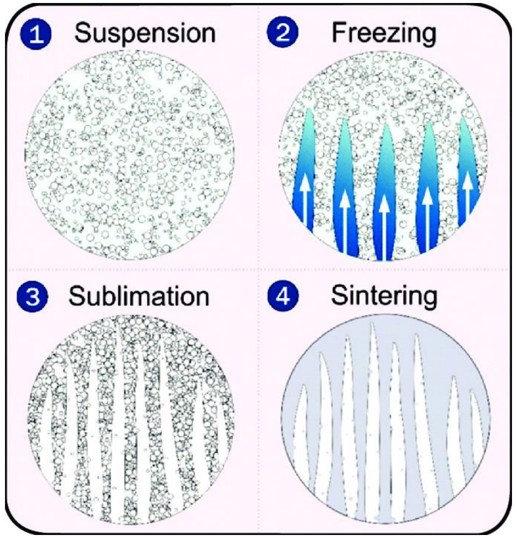


Source: [XX3d print] URL: https://www.ehu.eus/en/web/campusa-magazine/-/3d-printing-of-starch-for-personalised-medicine-development; [XXschema] URL: https://www.sciencedirect.com/topics/materials-science/direct-ink-writing; [yellow] URL: https://link.springer.com/chapter/10.1007/978-981-16-8121-9_7

Structural materials – Starch 3D

- **Molding**
- Extrusion/Injection/Compression Molding of Thermoplastic Starch:
  - Processing starch with plasticizers under high temperature and shear to form thermoplastic starch granules or pellets.
  - Using conventional plastic processing (extrusion or injection molding) to shape 3D objects (e.g., packaging trays, disposable cutlery).
  - Cooling the shaped product to yield a solid, starch-based rigid structure.
- Freeze-Casting and Porous Structures:
  - Preparing a starch hydrogel and freezing it to form ice templates
  - Freeze-drying (lyophilization) to remove ice and create porous, lightweight 3D starch scaffolds (useful in biomedical applications, filters, or lightweight packaging).
- Foaming and Baking (Biodegradable Packaging):
  - Introducing blowing agents or using water vapor expansion during extrusion of starch-based materials.
  - Creating starch foams or puffed structures with low density and protective cushioning properties (e.g., loose-fill packaging peanuts).
  - Baking or heat setting can help fix the shape and structure

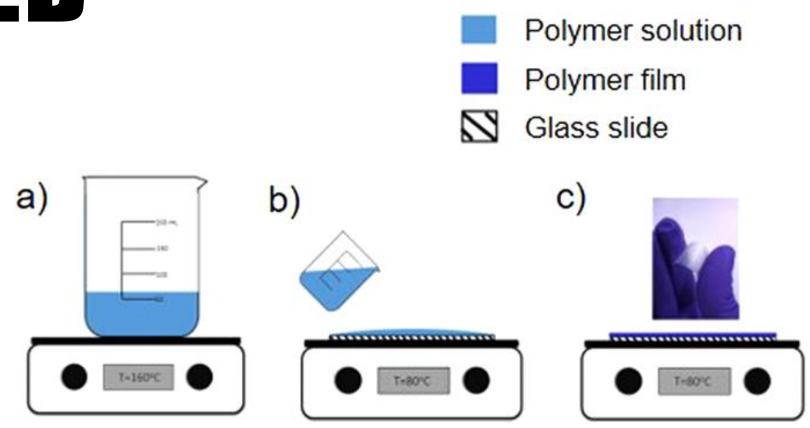




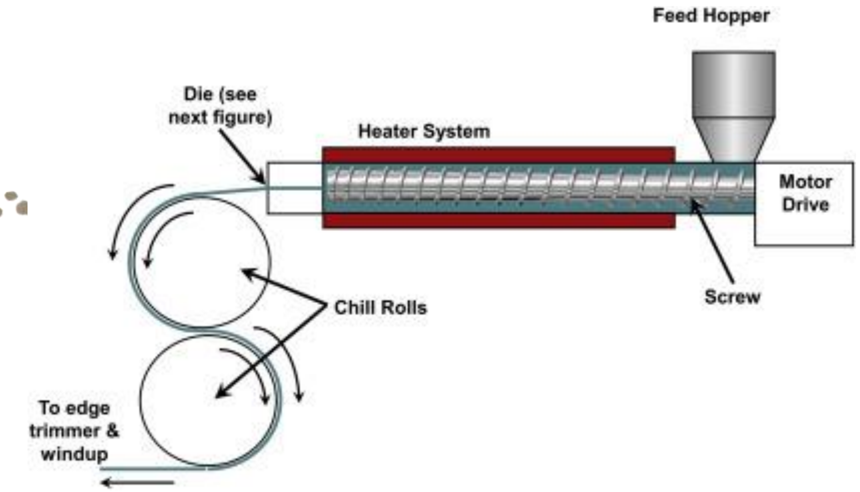
Source: [molding] URL: https://connect.nissha.com/ecosense/molding/en/pulpmold/; ; [freezecast] URL: https://www.researchgate.net/figure/Schematic-of-the-steps-of-the-freeze-casting-method_fig2_349175890; [XXfoam] URL: https://www.researchgate.net/publication/224829332_Starch_Protective_Loose-Fill_Foams

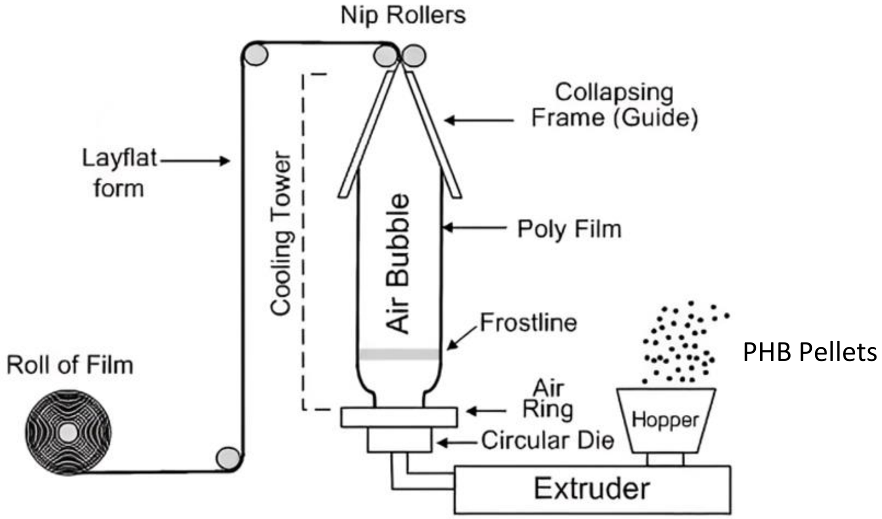
Structural materials – PHB 2D

- Solution Casting (Solvent Casting)
  - Dissolving PHB in an appropriate solvent (commonly chloroform or other halogenated solvents)
  - Casting the solution onto a flat surface (e.g., glass or Teflon) and evaporating the solvent
  - Producing relatively uniform, transparent films with tunable thickness



- Melt Extrusion and Blown Film Extrusion
  - Melting PHB pellets and extruding them through a flat die or using a blown film process
  - Adjusting temperature, screw speed, and film drawing rate to control film thickness and properties
  - Suitable for scalable, continuous production of packaging films

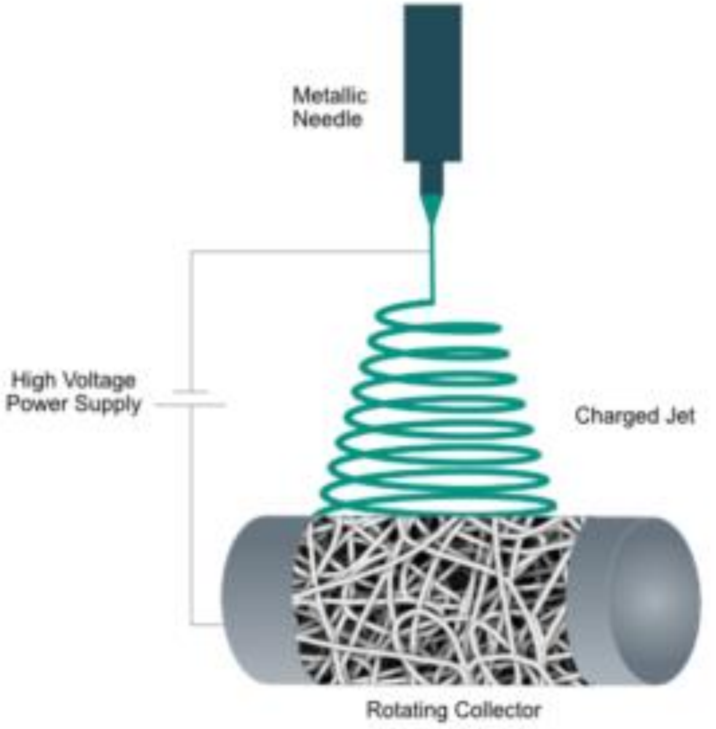




Source: [XX Pellets] URL: https://shop.helianpolymers.com/products/pb3000g-phb-pellets; [XXcasting] URL: https://www.researchgate.net/figure/Schematic-of-PHB-film-preparation-by-solvent-casting-a-The-PHB-is-dissolved-in-acetic_fig11_286236119; [XXextrusion] URL: https://www.sciencedirect.com/topics/engineering/melt-extrusion; [blow] URL: https://europlas.com.vn/en-US/blog-1/3-layer-blown-film-extrusion-process

Structural materials – PHB 2D

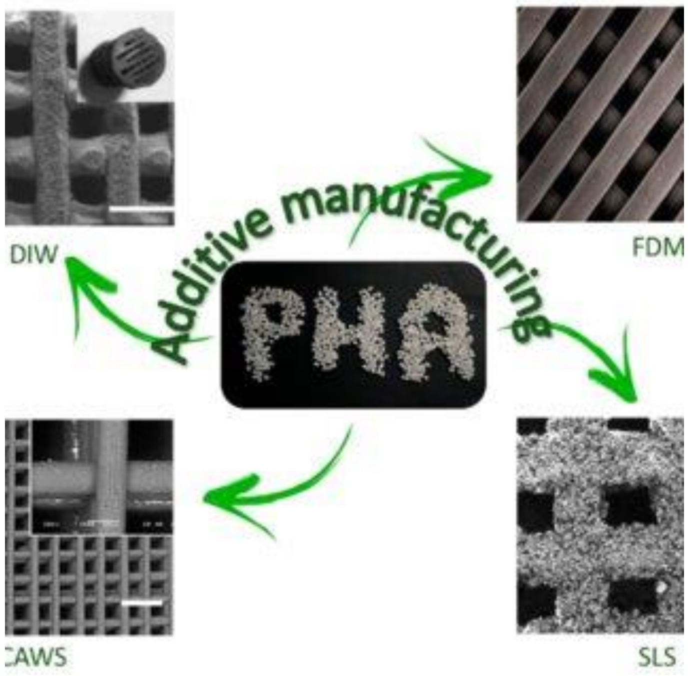
- Compression Molding of Films
  - Placing PHB granules or powders between heated plates and applying pressure.
  - Melting and pressing the polymer to form thin sheets or films
  - Cooling under pressure to obtain a solid, uniform film
- Electrospinning (for Nanofiber Mats)
  - Although this typically yields fibrous mats rather than dense films, electrospinning PHB solutions can produce ultra-thin membranes
  - The resulting structures can be densified or combined into film-like layers suitable for specialized filtration or biomedical applications

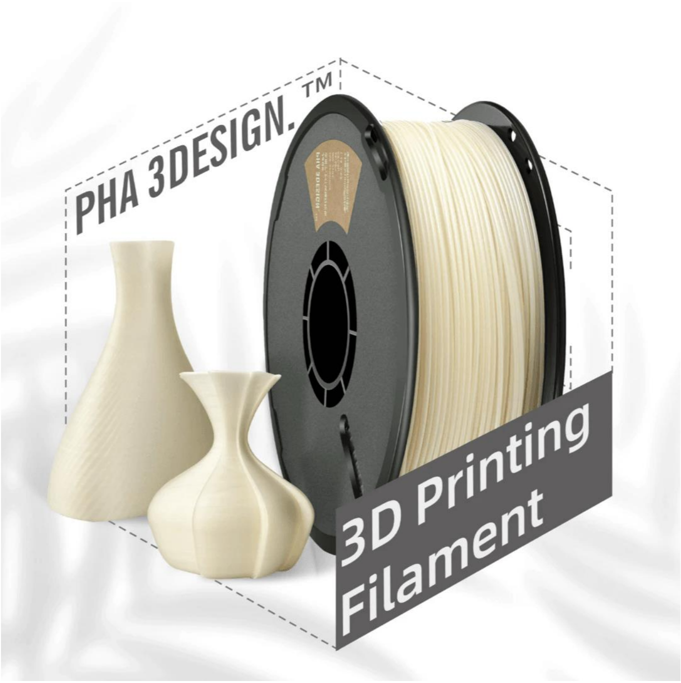


Source: [XXpress] URL: https://carverpress.com/presses-accessories/pnp-series-pneumatic-presses/; [XXelectrospinning] URL: https://www.electrospinning.co.uk/science/electrospinning/

Structural materials – PHB 3D

- **3D printing**
- 3D Printing
  - Processing PHB into filaments compatible with standard 3D printers
  - Printing layer-by-layer at controlled temperatures to build custom 3D shapes (prototypes, medical devices, consumer products)
  - Suitable for mass production of biodegradable components such as packaging items, consumer goods, and medical devices





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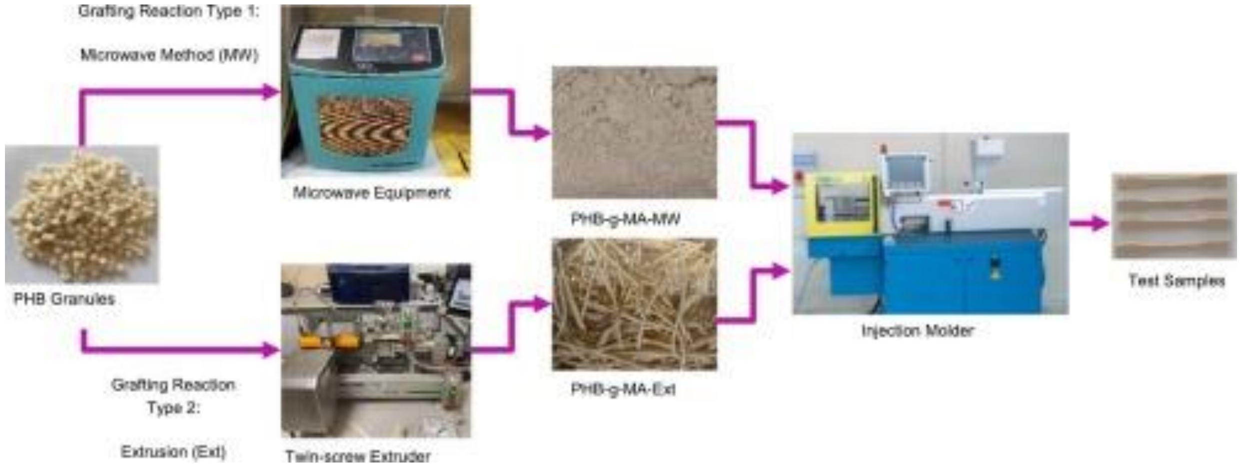
Source: [pha] URL: https://www.researchgate.net/figure/SEM-images-of-PHA-scaffolds-3D-printed-with-different-AM-techniques-a-PHBH-scaffolds_fig5_349541960; [XX3d print] URL: https://www.sbsgenetech.com/pha-3d-printing-filament

Structural materials – PHB 3D

- **Molding**
- Injection/compression Molding
  - Melting PHB pellets and injecting them into a mold cavity under high pressure.
  - Cooling and solidification result in 3D parts with potentially complex geometries
  - Suitable for mass production of biodegradable components such as packaging items, consumer goods, and medical devices

- Extrusion of Profiles and Sheets:
  - Continuous extrusion of PHB into various profiles (rods, tubes) or thick sheets
  - Subsequent thermoforming of extruded sheets into 3D objects (e.g., trays, cups, containers)
- Foaming and Porous Structures:
  - Using blowing agents or supercritical CO_2 to create foamed PHB structures
  - Producing lightweight, porous 3D forms useful in packaging, insulation, or tissue engineering scaffolds



Source: [Xxbottle] URL: https://www.ptonline.com/articles/processing-characteristics-of-phapla-blends-in-blow-molding, [extrusion] URL: https://www.sciencedirect.com/science/article/pii/S0141813024015496

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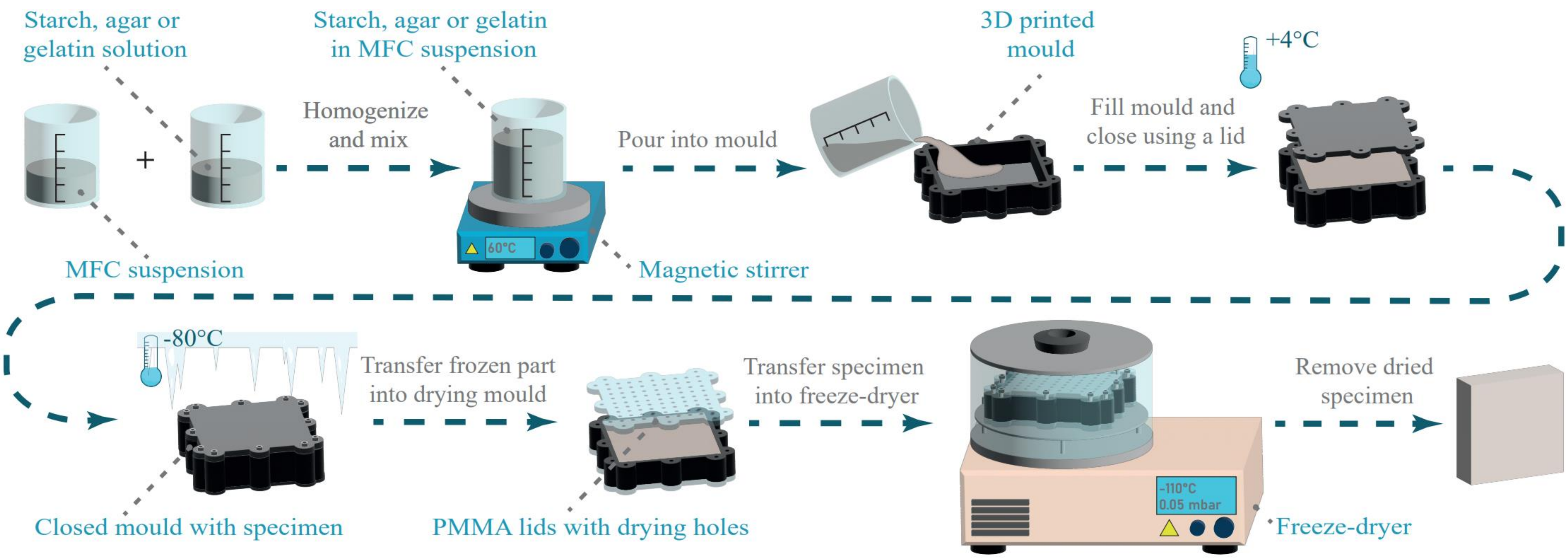
Research example – Airframe Manufacturing

- Drone's body:
  - Freeze dried (lyophilized) cellulose composite foam in a wing shaped mold
  - Requirements: Maximize strength-to-weight and stiffness-to-weight ratio



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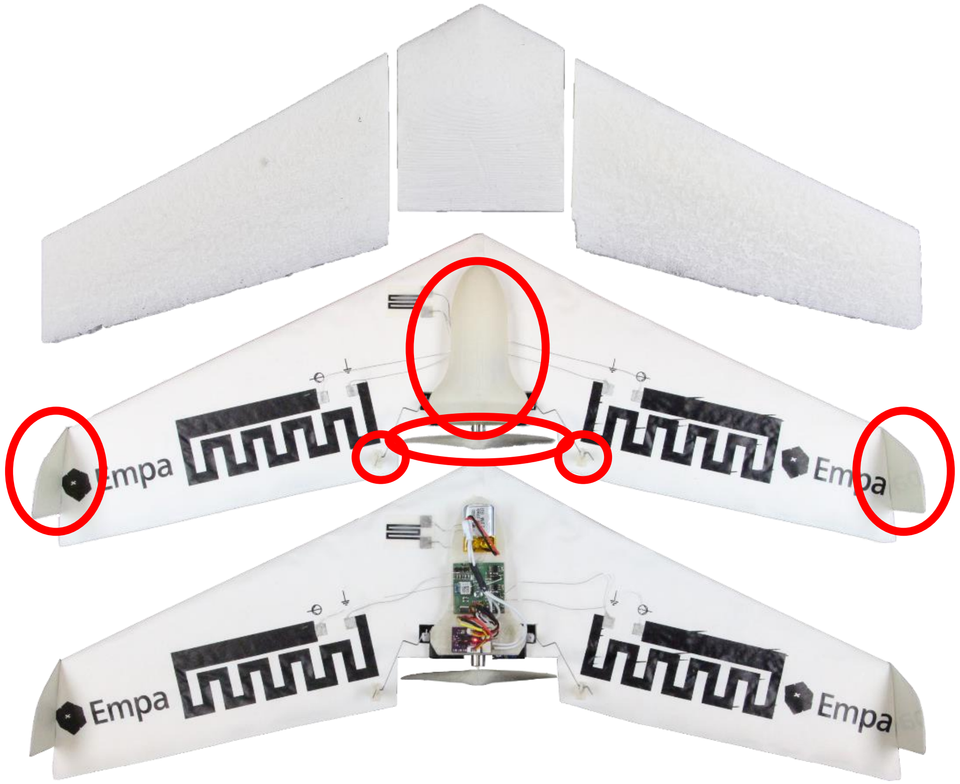
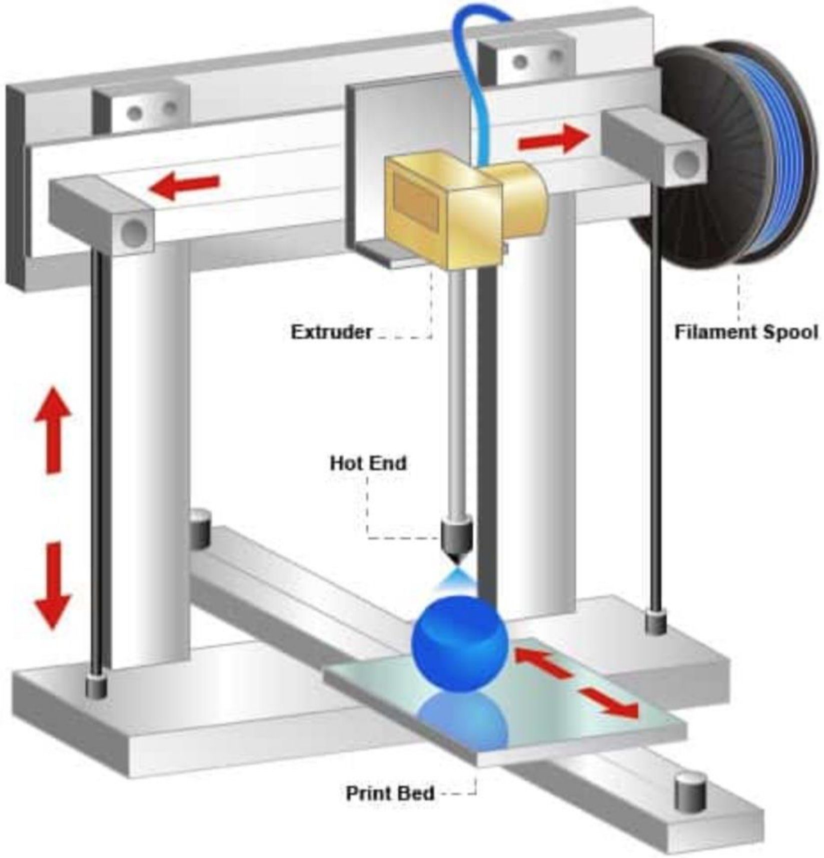
Research example – Airframe Manufacturing

- Drone's electronics compartment (marked red):
  - Conventional 3D printing (FDM) of PHA filament
  - Requirements: Maximize toughness





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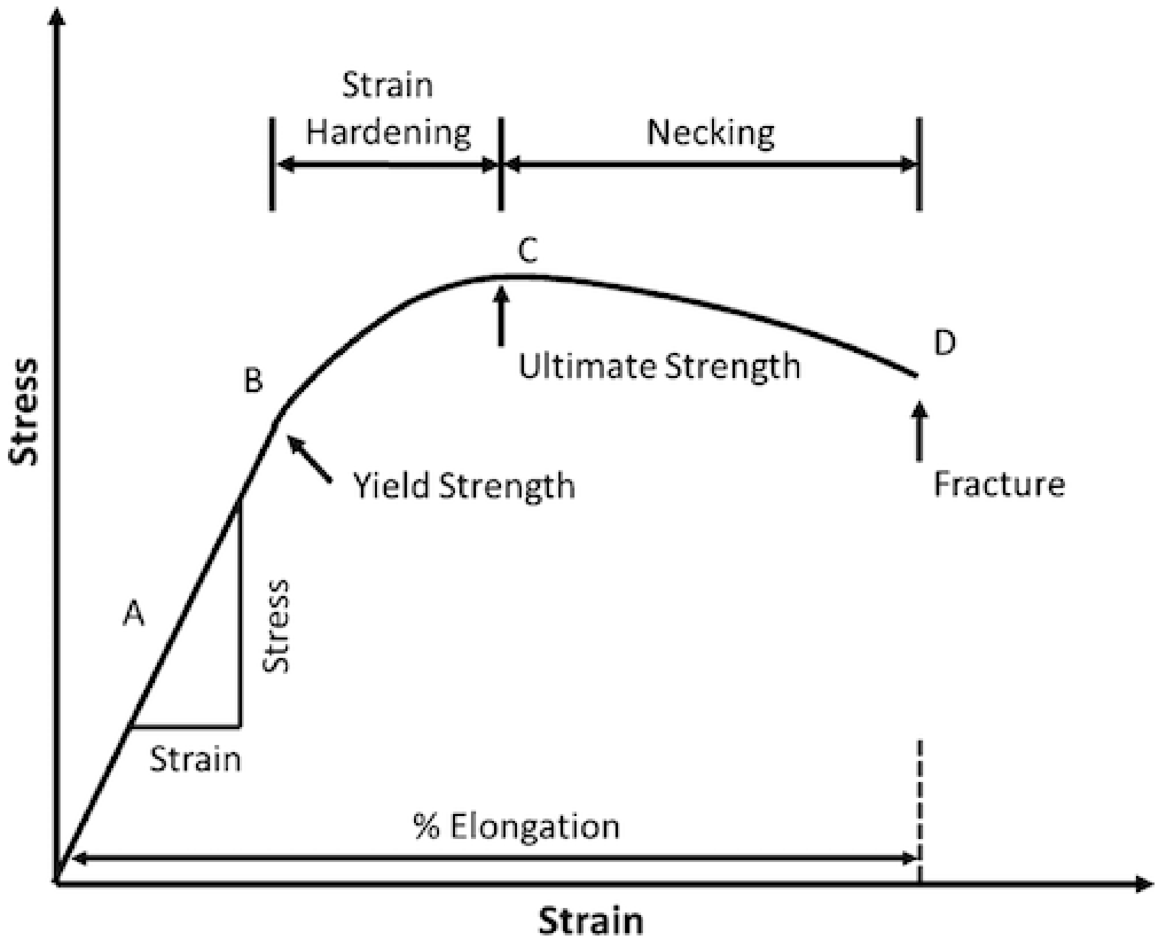
Structural Characterization

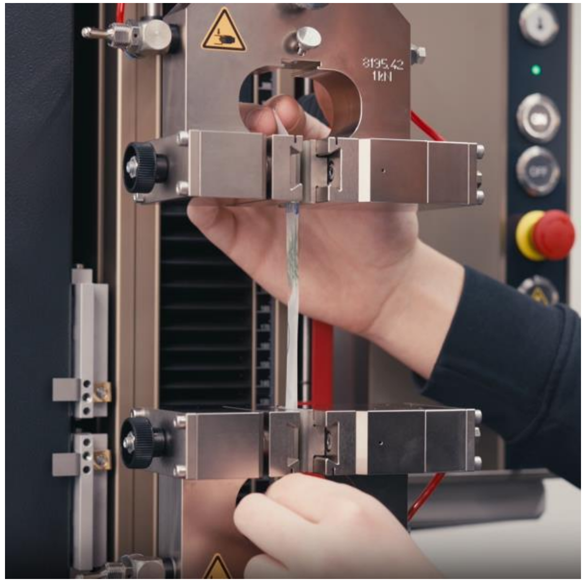
- Mechanical characterization:
  - Generally goal is to maximize the **strength** and **stiffness** of your design
  - When building aerial systems, the strength-to-weight and stiffness-to-weight ratio is maximized
  - Depending on the load case various mechanical properties can be investigated



Source: [XXplot] URL: https://courses.cit.cornell.edu/mclaskey/cee3710/stimulation3/strengthStiffness2018.html

Structural Characterization

- Mechanical characterisation of films:
  - Tensile Testing:
    - What It Measures: Tensile strength, Young’s modulus, and elongation at break.
    - Relevance: Evaluates film’s ability to withstand forces that stretch it, reflecting its durability and flexibility.
    - Standards & Equipment: Often follows ASTM D882 or ISO 527 using a universal testing machine. Film strips are pulled at a constant rate until failure.
    - Reported Values:
      - Tensile Strength (MPa) – Maximum stress before breaking
      - Elongation at Break (%) – Ductility or stretchability
      - Young’s Modulus (MPa) – Stiffness or rigidity

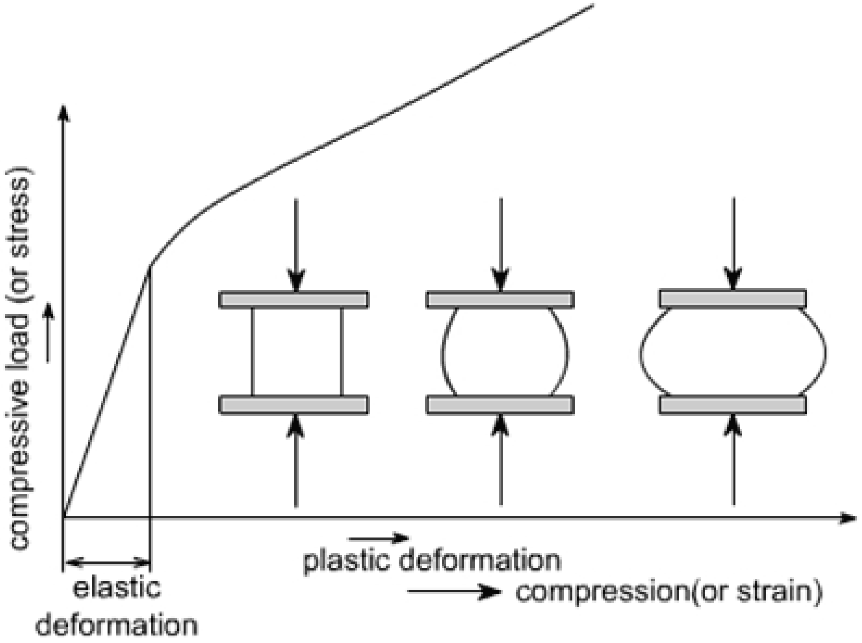


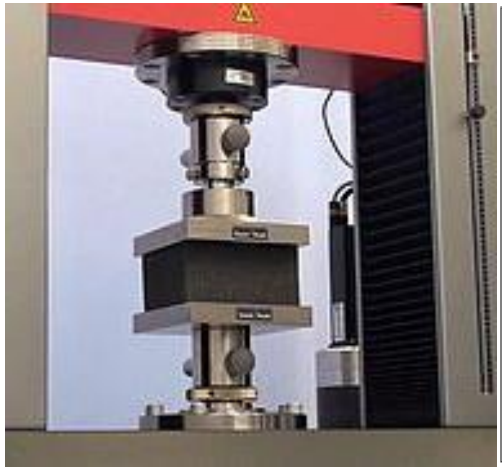
  - Tear Resistance Tests:
    - What It Measures: Resistance to propagation of a tear once initiated.
    - Relevance: Critical for packaging films and membranes that must resist damage during handling.

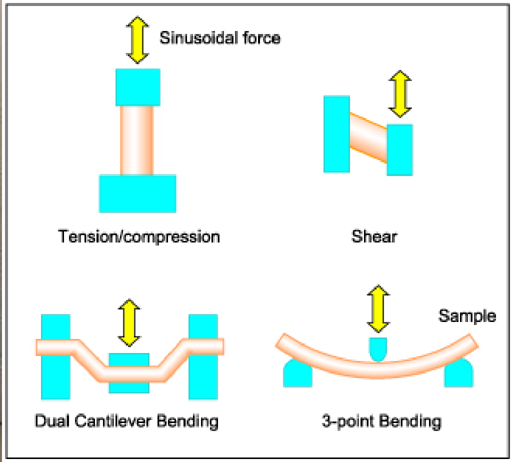
Source: [XXplot] URL: https://courses.cit.cornell.edu/mclaskey/cee3710/stimulation3/strengthStiffness2018.html; [Xxtensile] URL: https://www.zwickroell.com/industries/plastics/thin-sheeting-and-plastic-films/tensile-properties-iso-527-3/; [Xxtear] URL: https://www.instron.com/en/testing-solutions/iso-standards/iso-6383-1

Structural Characterization

- Mechanical characterisation of foams (and other 3D materials):
  - Compressive Testing:
    - What It Measures: Compressive strength, modulus, and energy absorption under load.
    - Relevance: Evaluates the foam’s capacity to withstand forces that push it together, simulating handling, stacking, and impact conditions..
    - Standards & Equipment: Often follows ASTM D1621 using a universal testing machine. Specimens compressed between parallel plates at a constant rate.
    - Reported Values:
      - Compressive Strength (kPa or MPa): Stress at a specified strain (often 10%, 25%, or at densification).
      - Compressive Modulus: Slope of the stress-strain curve in the linear elastic region, indicating stiffness.
      - Energy Absorption: Area under the stress-strain curve, reflecting cushioning capability.
  - Dynamic Mechanical Analysis (DMA):
    - What It Measures: Viscoelastic behavior (storage modulus, loss modulus) under oscillatory load.
    - Relevance: Assesses foam’s mechanical response to cyclic stresses and temperature changes.







Source: [XXplot] URL: https://www.zwickroell.com/industries/materials-testing/compression-test/; [Xxcomp] URL: https://www.zwickroell.com/industries/materials-testing/compression-test/; [Xxdma] URL: https://www.hitachi-hightech.com/global/en/knowledge/analytical-systems/thermal-analysis/basics/dma.html

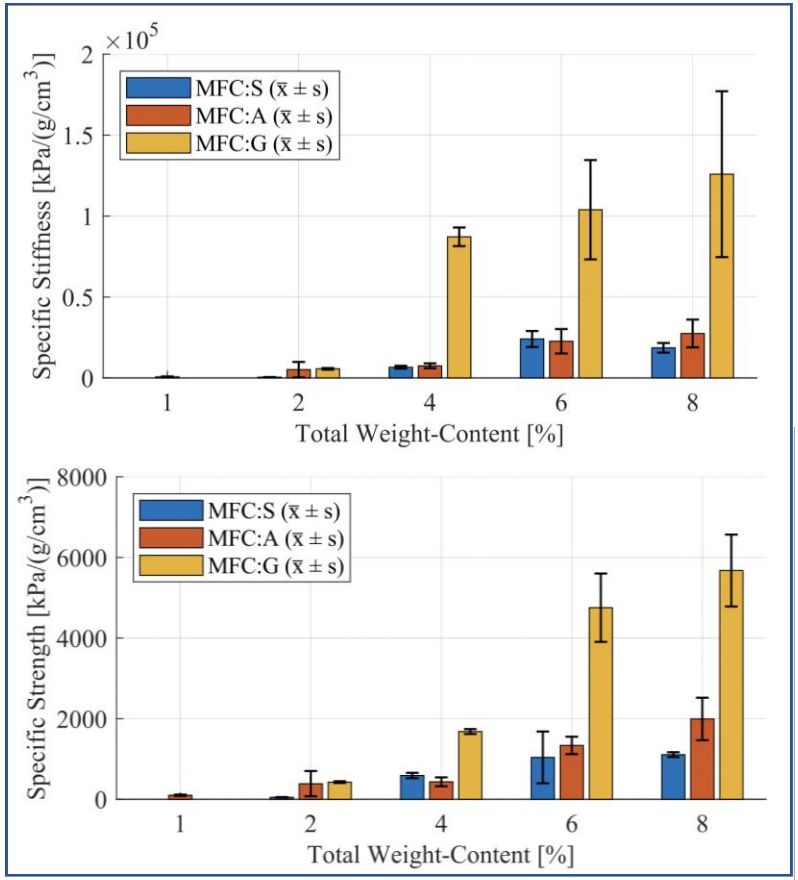
Structural Characterization

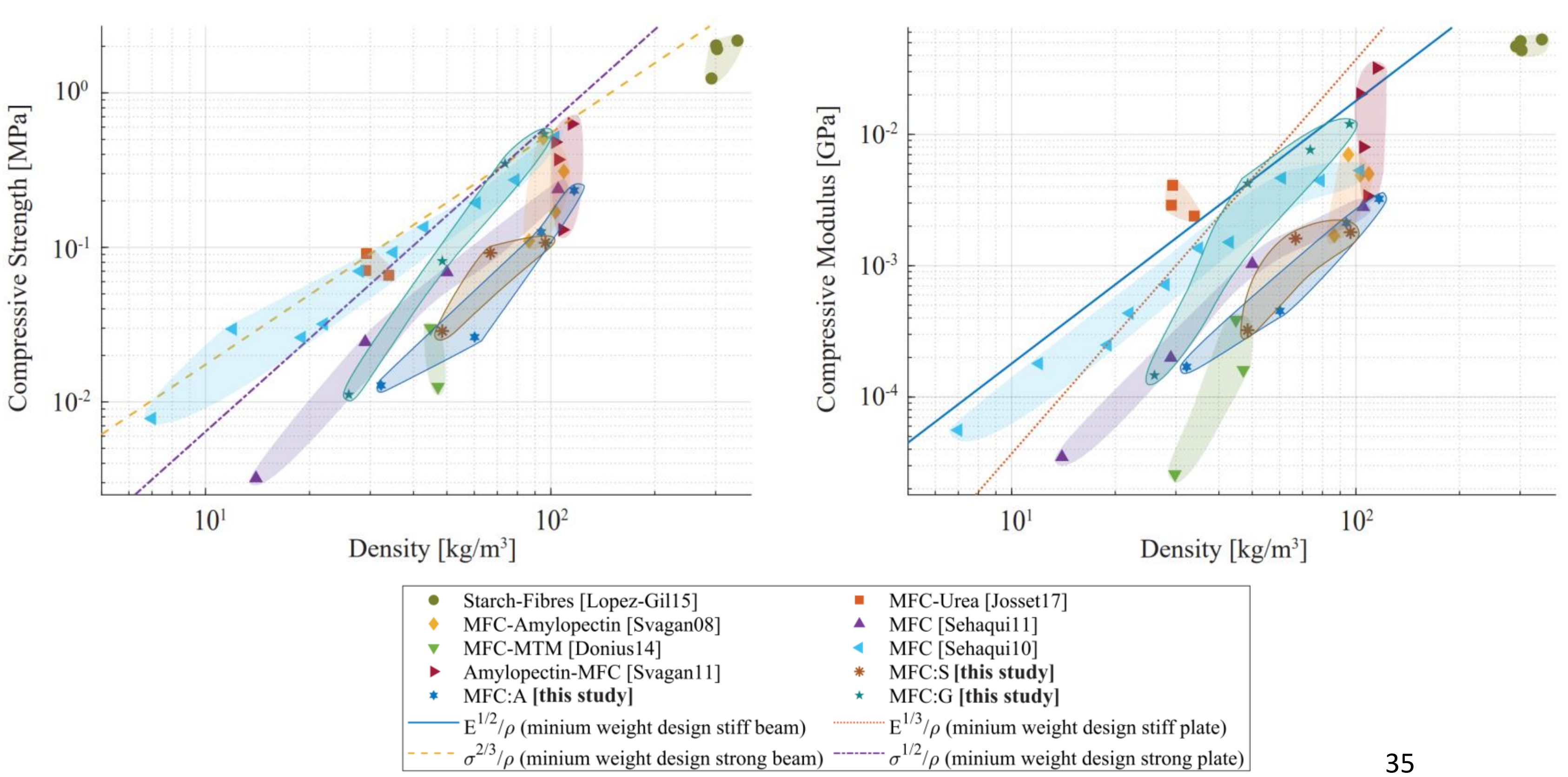
- Application specific testing:
  - Flexural (bending) testing:
    - What It Measures: Flexural strength, flexural modulus, and deflection at break.
    - Relevance : Evaluates the material's ability to resist deformation under bending loads, simulating conditions in beams, sheets, and structural components.
    - Standards & Equipment: Sample placed in a climate-controlled chamber. Humidity is incrementally increased or decreased while measuring sample mass changes in real-time.
    - Reported Values:
      - Moisture sorption isotherms
      - Sorption/desorption kinetics
      - Equilibrium moisture content at different RH levels
  - All of the above discussed mechanical tests at certain temperature and humidities

Source: [3pb] URL: https://www.bruker.com/en/products-and-solutions/test-and-measurement/tribometers-and-mechanical-testers/3-point-bend-testing.html

Research example – Structural Testing

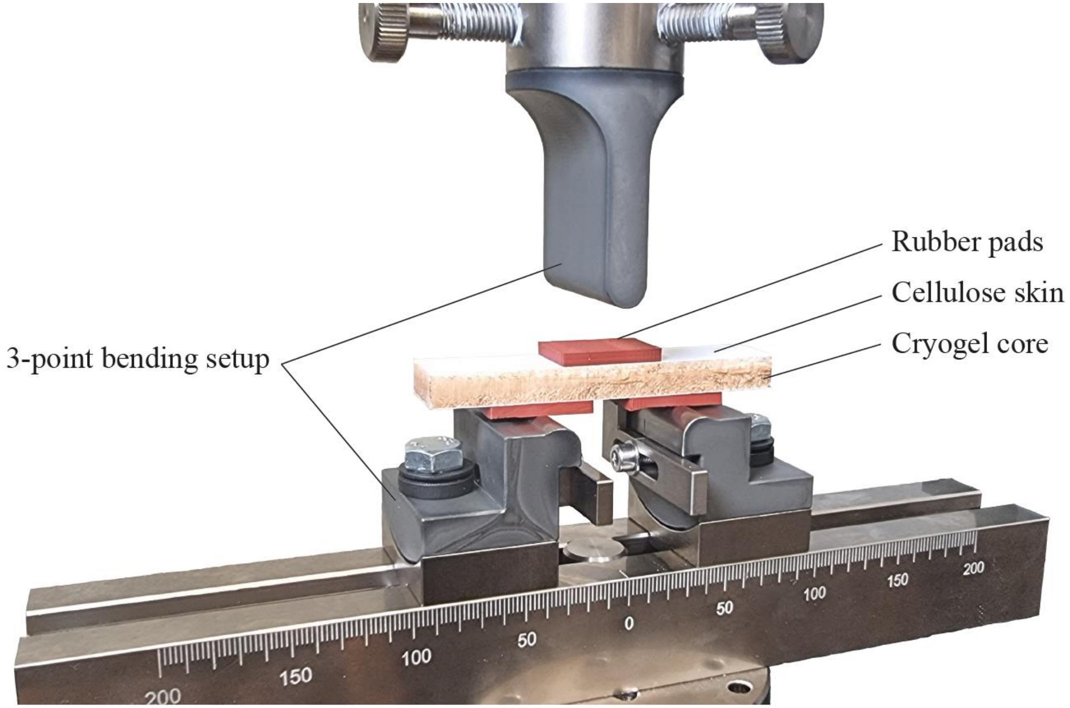
- Drone's wing:
  - Investigating structural performance of cellulose composite cryogels using compressive testing
  - Visualisation using Ashby plot (2D plot comparing materials properties)
    - Here the density and compressive strength and compressive moduls are visualised
  - Result: Cellulose-gelatin cryogel outperforms the other composites





Research example – Structural Testing

- Drone's wing:
  - Investigating added structural performance of cellulose composite reinforced with celluloe substrate as "skin"
  - Achieving a high performance sandwich structure
  - Result:
    - Samples w/o face sheets:
    - $E_B = 4849\ MPa\ (s = 706\ MPa)$
    - $\sigma_{fM} = 1.09\ MPa\ (s = 0.25\ MPa)$
    - Samples w. face sheets:
    - $E_B = 13585\ MPa\ (s = 2491\ MPa)$
    - $\sigma_{fM} = 2.15\ MPa\ (s = 0.25\ MPa)$
    - Flexural stiffness increased by 2.80 x
    - Flexural strength increased by 1.97 x
    - Weight increased only by 1.31 x



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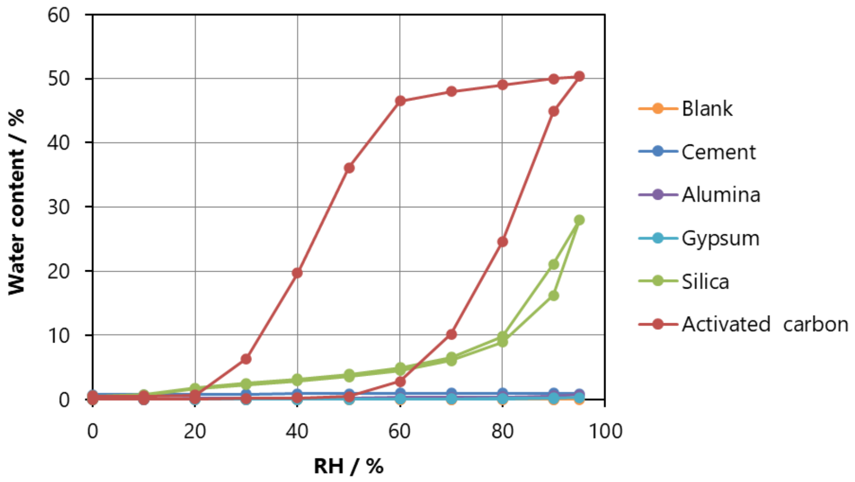
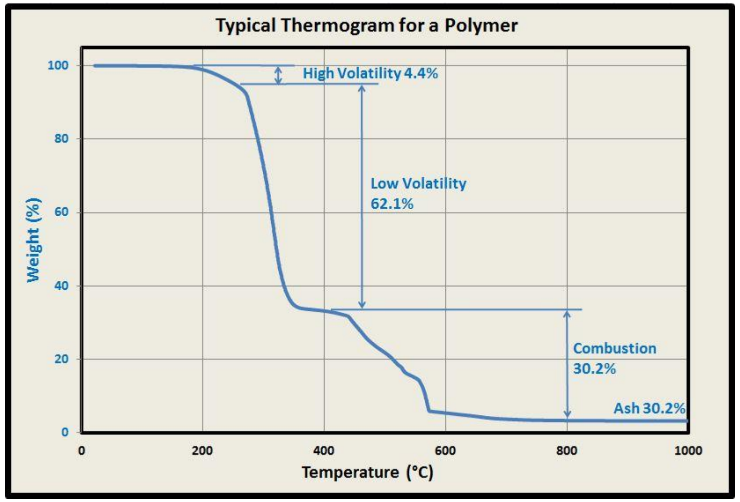
Environmental Characterization

- Environment specific testing:
  - Dynamic Vapor Sorption (DVS):
    - What It Measures: Changes in mass as the material is exposed to varying humidity levels at controlled temperatures.
    - Relevance: Determines moisture uptake, diffusion behavior, and equilibrium moisture content—critical for predicting dimensional stability, mechanical performance, and degradation rates.



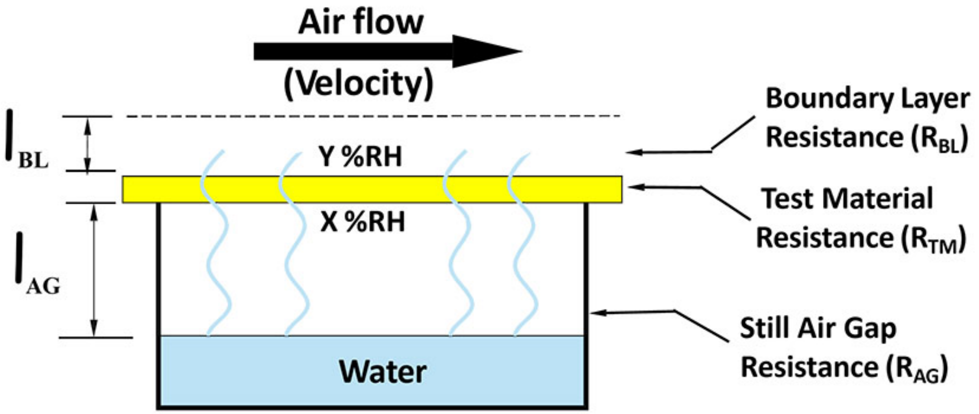
  - Thermogravimetric Analysis (TGA) with Humidity Control:
    - What It Measures: Mass changes due to thermal decomposition under controlled humidity.
    - Relevance: Reveals how moisture influences thermal stability and degradation onset temperatures.



Source: [XXplot] URLhttps://www.norlab.com/library/overview-article/13395; [Xxmachine] URL: https://www.az2om.com/equipment-details.aspx?EquipID=4076; [Xxmachine2] URL: https://en.wikipedia.org/wiki/Thermogravimetric_analysis#/media/File:Thermogravimetric_analyser.jpg; [Xxplot] URL: https://www.lpdlabservices.co.uk/analytical_techniques/chemical_analysis/tga_interpret.php

Environmental Characterization

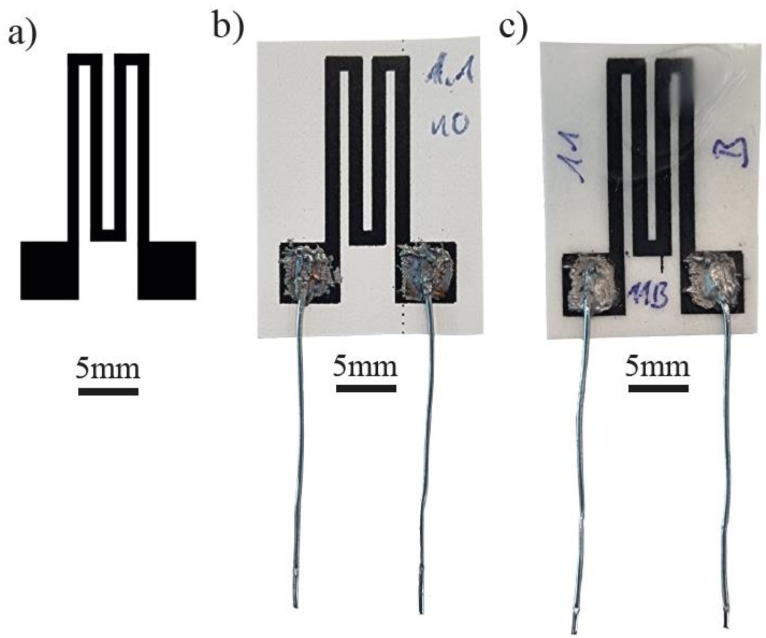
- Water Vapor Transmission Rate (WVTR) Tests:
  - What It Measures: Rate at which water vapor passes through a material's surface.
  - Relevance: Critical for packaging applications to ensure product protection under varying humidity.

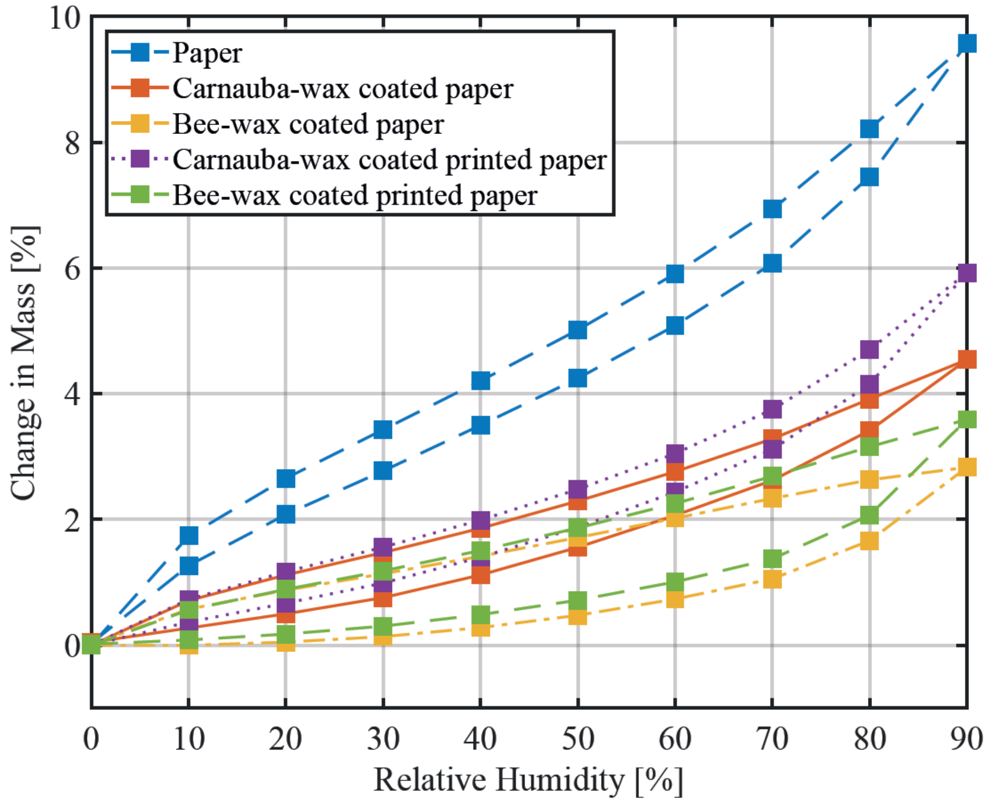


Source: [XxWVTR] URL: https://www.nonwovens-industry.com/buyersguide/profile/ametek-mocon/view_how-to-test-water-vapor-transmission-rate-through-nonwoven-materials/

Research example – Humidity uptake

- DVS testing of substrate for printed temperature sensor
  - Investigation of waterproofing capabilities of different bio-based coating materials (bee wax and carnauba wax)
  - Result: Bee wax reduce the water uptake better





Source: [XX2glasses] paper

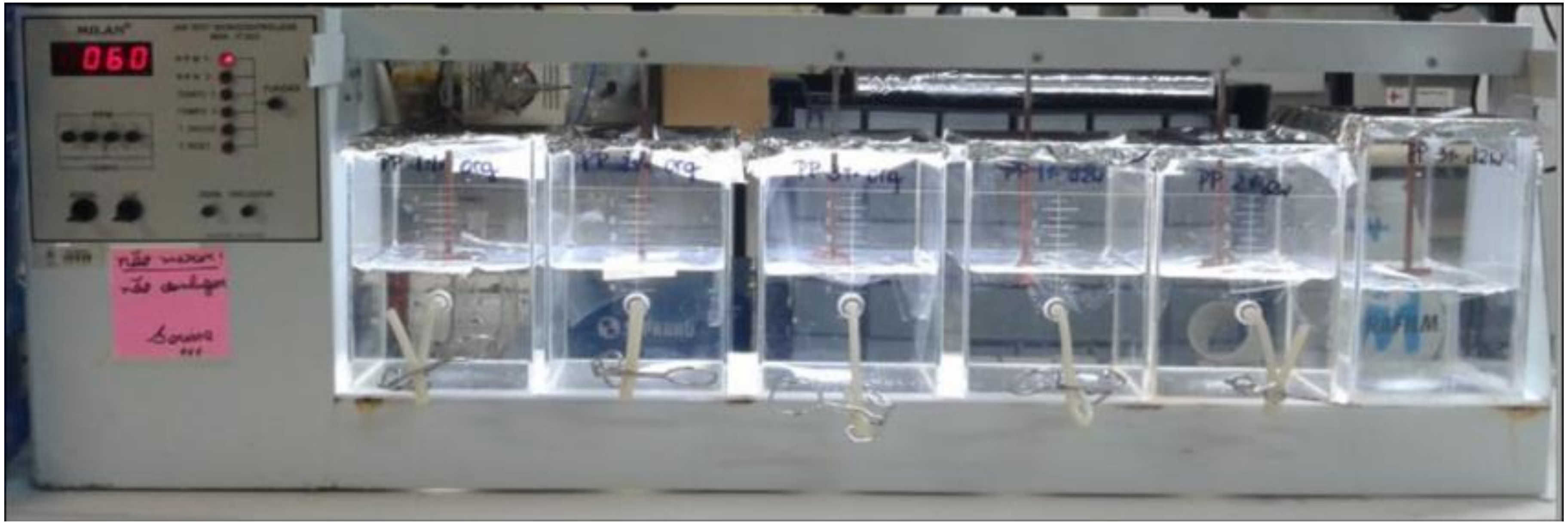
Biodegradation Characterization

- Biodegradation testing:
  - Standardized Composting Tests (e.g., ASTM D5338, ISO 14855):
    - What It Measures: CO_2 evolution under controlled aerobic composting conditions.
    - Relevance: Indicates how a material breaks down into carbon dioxide, water, and biomass in an industrial composting environment.
    - Standards & Equipment: Material mixed with compost and kept at ~58°C and controlled humidity.CO_2 emissions monitored over time until plateau, indicating extent of biodegradation.
  - Soil Burial Tests (e.g., ASTM D5988):
    - What It Measures: Biodegradation in natural soil conditions.
    - Relevance: Reflects real-world degradation rates in agricultural or landfill environments
    - Standards & Equipment: Samples buried in soil with controlled moisture and temperature.CO_2 evolution, mass loss, and visual changes evaluated periodically.

Source: [XX2glasses] URL: https://www.situbiosciences.com/product/astm-d5338-biodegradation-test-composting/

Biodegradation Characterization

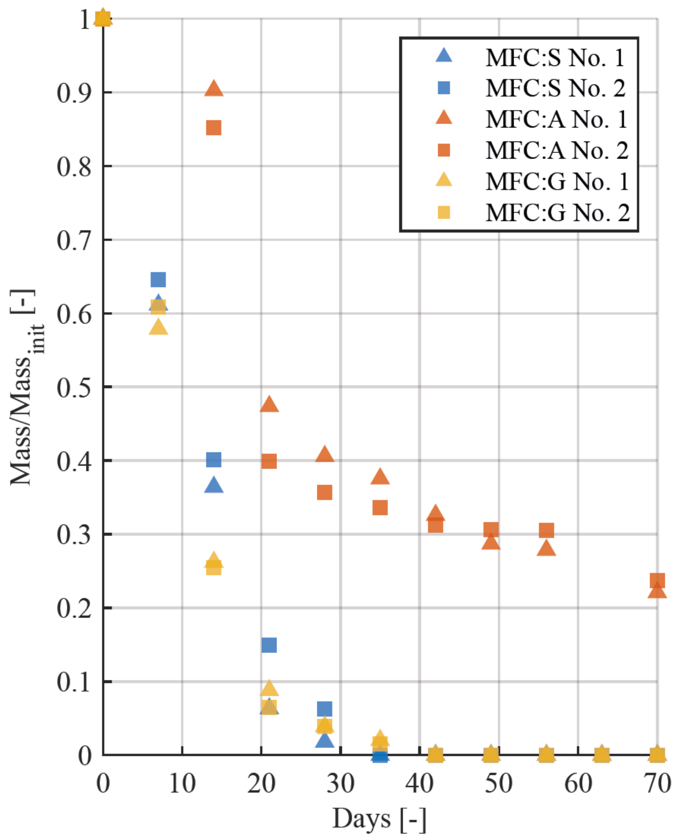
- Marine and Freshwater Tests (e.g., ASTM D6691):
  - What It Measures: Biodegradation in aquatic environments.
  - Relevance: Essential for materials likely to enter marine ecosystems.
  - Standards & Equipment: Exposure to seawater and marine microorganisms. Monitoring CO_2 production, mass loss, or fragmentation over time.

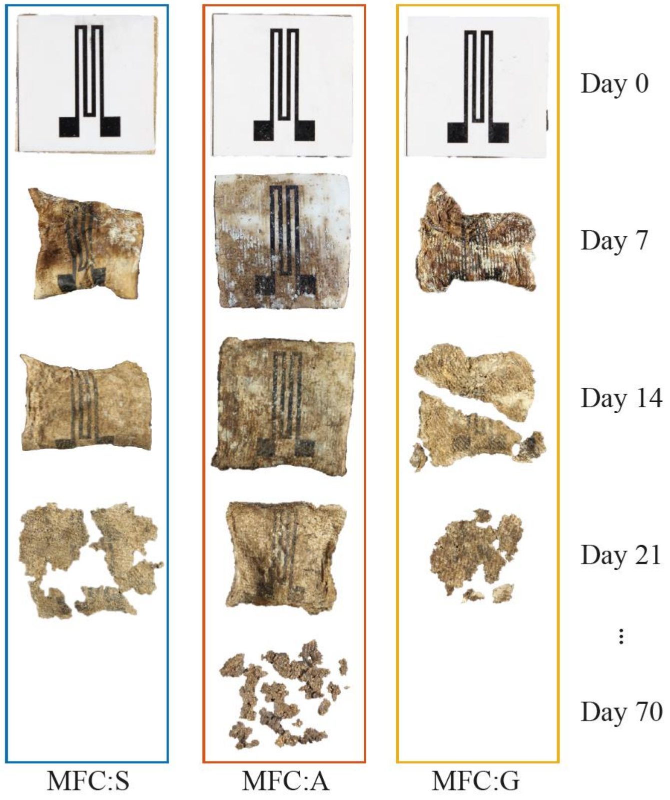


Source: [XXwater] URL: https://www.researchgate.net/figure/Biodegradation-in-simulated-marine-water-test_fig1_304875885/

Research example – Biodegradation

- Biodegradation testing using a soil demonstrator:
  - Keeping cryogel samples in sawdust, rabbit feed, cornstarch, sugar, corn oil, urea, and compost at const. 58°C
  - Measuring the weight loss over time
  - Result: Cellulose-starch and Cellulose-gelatin composites have the fastest biodegradation rate





Source: [XX2glasses] paper

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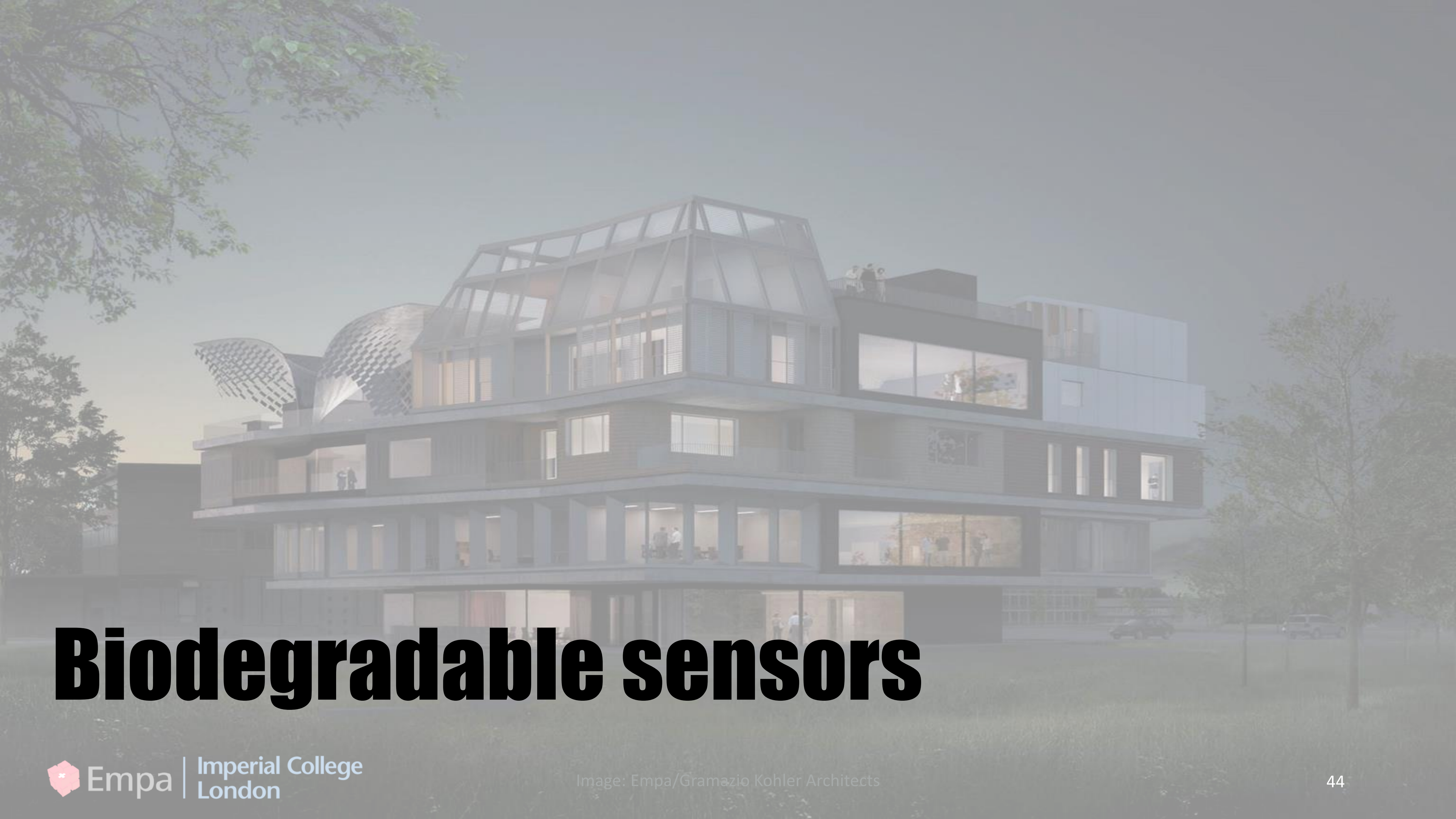
Break



Biodegradable sensors

Image: Empa/Gramazio Kohler Architects

Biodegradable sensors – Materials

- Material Considerations:
  - Organic and Natural Polymers:
    - Silk fibroin
    - Cellulose
    - Chitosan
    - Polyhydroxybutyrate (PHB)
    - Starch etc.
  - Biocomposites:
    - Combining biopolymers with natural fillers (e.g., cellulose nanofibers, starch)
  - Functional Biomaterials:
    - Incorporation of conductive biomaterials (e.g., conductive polymers derived from polypyrrole) that can degrade or transform into benign byproducts
  - Material Properties:
    - Balancing conductivity, mechanical stability, and controlled degradation rates

Biodegradable sensors – Types & Fabrication

- Mechanisms of Sensing:
  - Electrochemical:
    - Measuring changes in current, potential, or ion transport in response to environmental stimuli
  - Mechanical/Structural:
    - Strain, pressure, and tactile sensors made from biodegradable elastomers
  - Optical/Biochemical:
    - Change in color or fluorescence intensity under certain conditions using natural pigments or enzymes
- Fabrication Techniques:
  - Printing (screen printing, inkjet etc.) with biodegradable inks
  - Layer-by-layer assembly using water-based processes (coating etc.)
  - Low-temperature or room-temperature curing to preserve biomaterial function

Biodegradable sensors – Considerations I

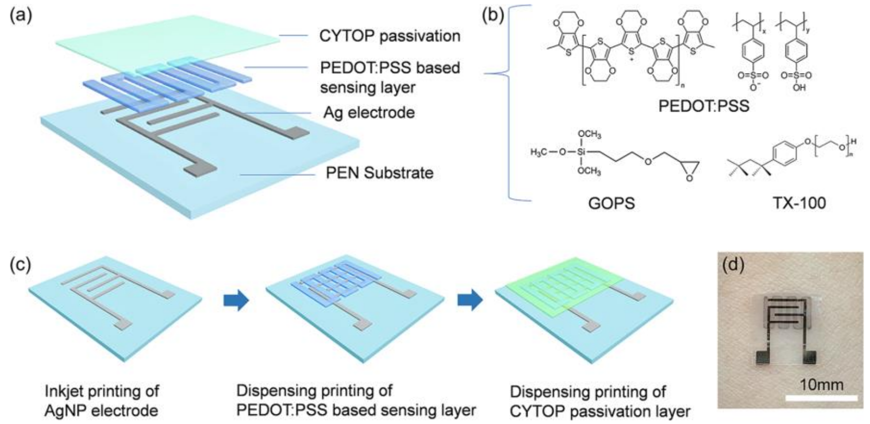
- Performance Challenges and Trade-Offs:
  - Stability vs. Biodegradability:
    - Ensuring functional lifespan matches the robot's operational window
    - before intentional degradation:
  - Sensitivity vs. Material Limitations:
    - Achieving high sensitivity and repeatability with materials that have variable natural properties
  - Integration with Electronic Circuits:
    - Embedding conductive paths and components that degrade while maintaining desired sensor response until end-of-life
    - Higher sensor sophistication with use of non-degradable electronics vs. more embodied sensing without additional electronics

Biodegradable sensors – Considerations II

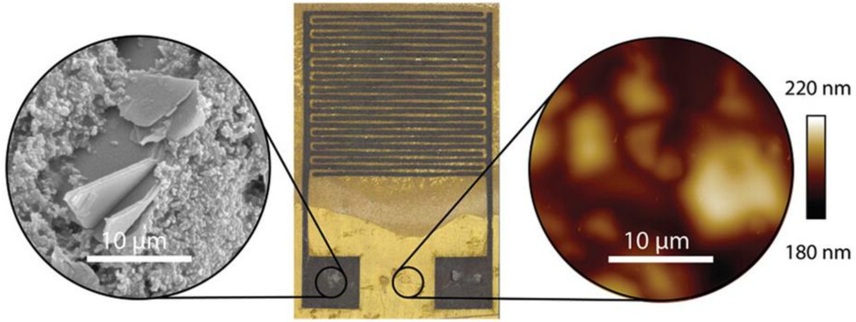
- Biodegradable vs. bioresorbable:
  - Biodegradable Materials:
    - Break down into simpler compounds under natural environmental conditions (with the help of microorganisms like bacteria and fungi).
    - Should entirely be used for transient robotics.
  - Bioresorbable Materials:
    - degrade specifically within a living organism and are absorbed or metabolized by the body.
    - Commonly used for in the medical field (implantation etc.)
    - Materials used: Polyglycolic Acid (PGA), Polycaprolactone (PCL), bioresorbable metals for electronics (Mg, Fe, Zn)
- Carbon conductive Materials:
  - Elemental carbon itself is not biodegradable
  - Biodegradation refers to the breakdown of complex organic molecules by living organisms, not simple elements.
  - Carbon atoms cycle through the environment (e.g., as CO_2), but the element itself doesn't "biodegrade" like organic compounds do.
  - Nevertheless, Carbon can eventually integrate into natural carbon cycles and is considered more sustainable.

Biodegradable sensors – Electrochemical

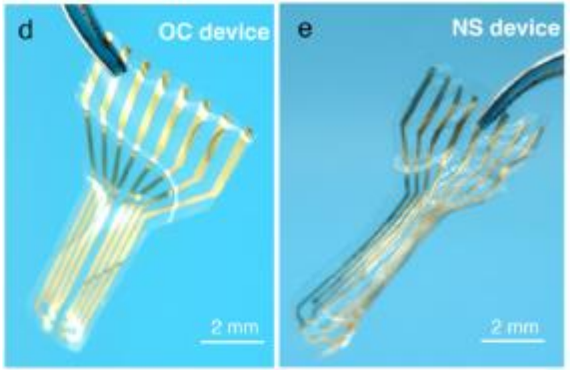
- Conductive Biopolymers:
  - Sensors integrating Polypyrrole or PEDOT:PSS on biodegradable substrates (e.g., cellulose, PHB) that measure ionic or chemical changes.
  - But: there an no conductive biopolymers proven to be biodegradable in all environments.
- Biodegradable Electrodes:
  - Biodegradable electrode arrays (e.g. silk fibroin or chitosan).
  - Use of carbon or bioresorbable metals as conductive elements.
- Applications:
  - Temporary wearable devices for short-term health diagnostics.
  - Soil nutrient monitoring tools that vanishafter a growing season.



Bacterial cellulose-polypyrrole strain sensor



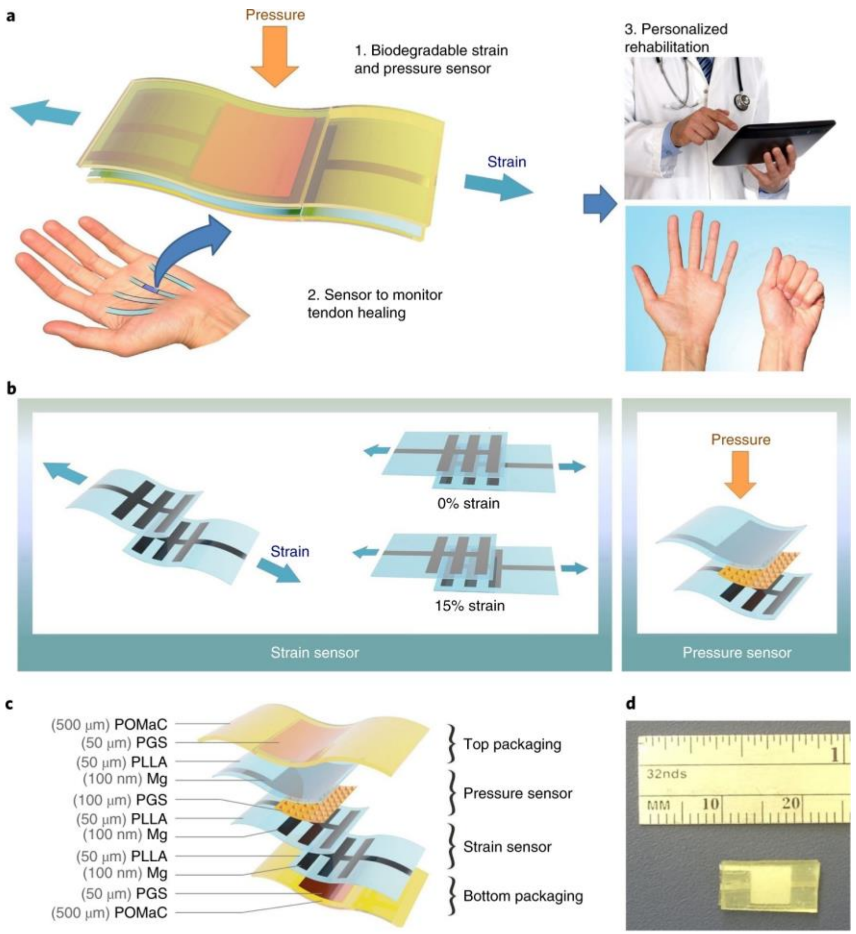
Carbon ink based humidity sensor



Source: [stretch] C. Gao, et al., Chem. Eng. Journal, 2023; [12] F. Wiesemüller, et al., Adv. Int. Sys., 2023; [13] A. Aeby, et al., Adv. Mat. Tech., 2022; [PEDOT] URL: https://www.nature.com/articles/s41598-020-59432-2/figures/1; [XXarray] URL: https://www.sciencedirect.com/science/article/pii/S0956566324008601

Biodegradable sensors – Mechanical

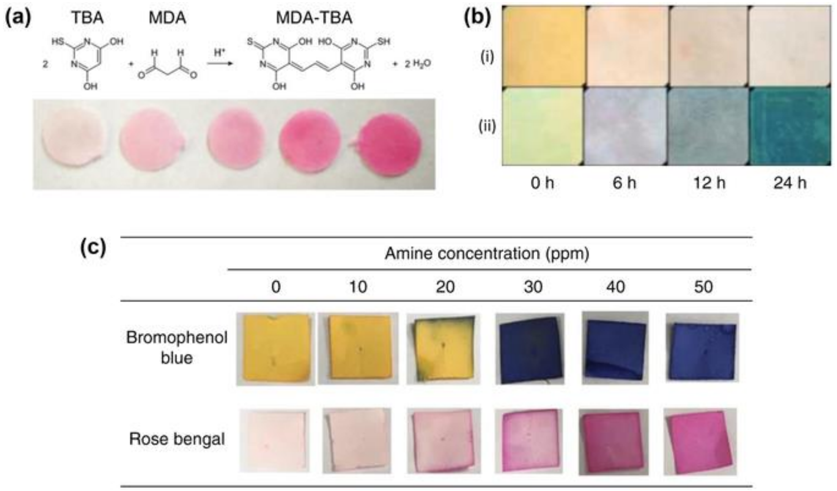
- Pressure & Strain Sensors:
  - PLA or cellulose-based thin films that respond to deformation and break down under environmental conditions.
  - Biodegradable elastomeric composites (e.g., starch-based) that measure force or strain in soft robotic components.
- Flexible Supports & Substrates:
  - Natural rubber or gelatin-based substrates that provide mechanical flexibility, degrade after fulfilling their sensing role.
- Applications:
  - Temporary agricultural robots that detect soil compaction and then degrade.
  - Disposable medical patches monitoring wound healing stress before dissolving harmlessly.

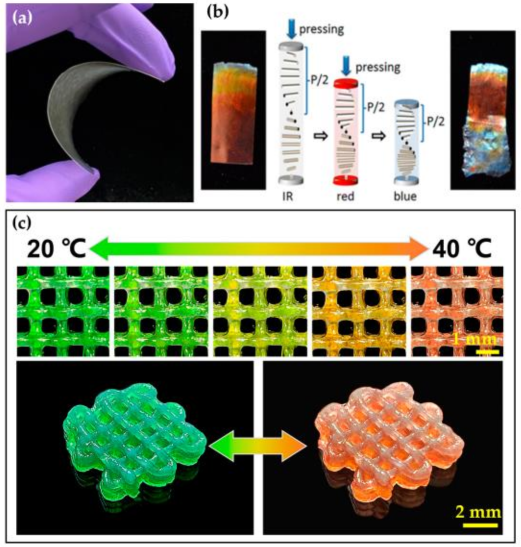


Source: [sensor] URL: https://www.nature.com/articles/s41928-018-0071-7#author-information

Biodegradable sensors – Optical

- Colorimetric Indicators:
  - Natural pigments (from beetroot, turmeric) embedded in dissolvable fibers, changing color in response to pH or contaminants.
- Fluorescent & Enzymatic Biosensors:
  - Enzyme-loaded silk films that produce fluorescence upon detecting specific biomolecules and then degrade over time.
  - Cellulose-based substrates with embedded indicator molecules that break down into harmless sugars.
- Photonic Structures:
  - Biodegradable photonic crystals (e.g., from cellulose nanocrystals) altering reflectance with humidity or temperature and later decomposing into benign byproducts.
- Applications:
  - Single-use environmental test strips that visually indicate pollutant levels and then compost.
  - Temporary implantable sensors that detect biochemical markers and dissolve within the body without removal.

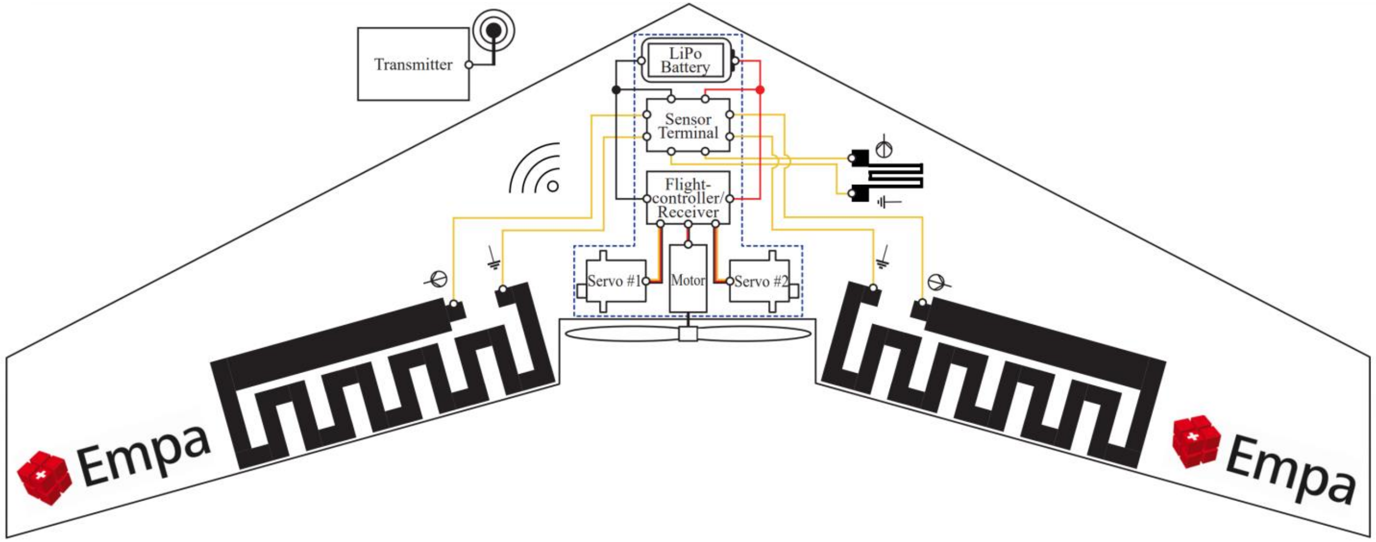


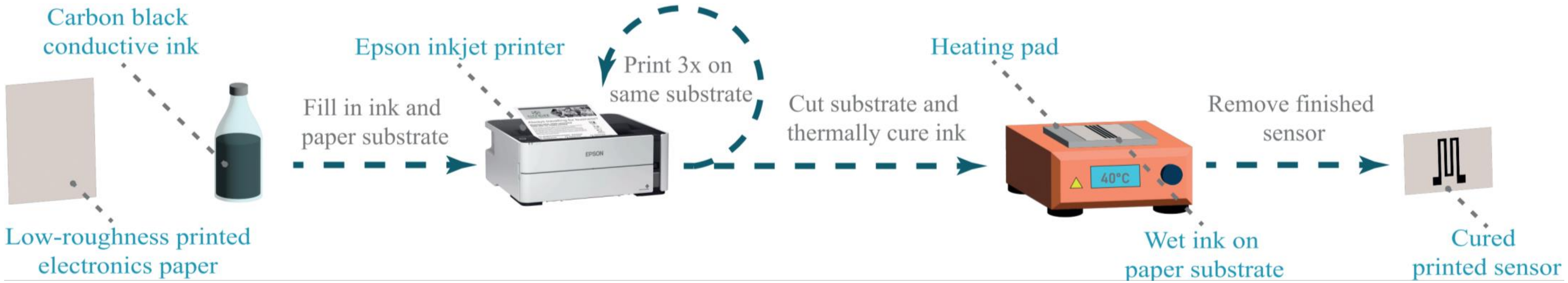


Source: [sensor] URL: https://www.researchgate.net/figure/Examples-of-colorimetric-indicators-fabricated-on-paper-based-substrates-through_fig2_359687338, [temp] URL: https://www.mdpi.com/2073-4352/13/7/1010

Research example – Incorporated Sensors

- Drone's sensing skin:
  - Carbon conductive ink with commercial ink-jet printer
  - Low-roughness electronics cellulose substrate (Arjowiggins)
  - Printed & heat-cured temperature and elevon sensors
- Result:
  - Low cost fabrication with minimal amount on non-degradable components





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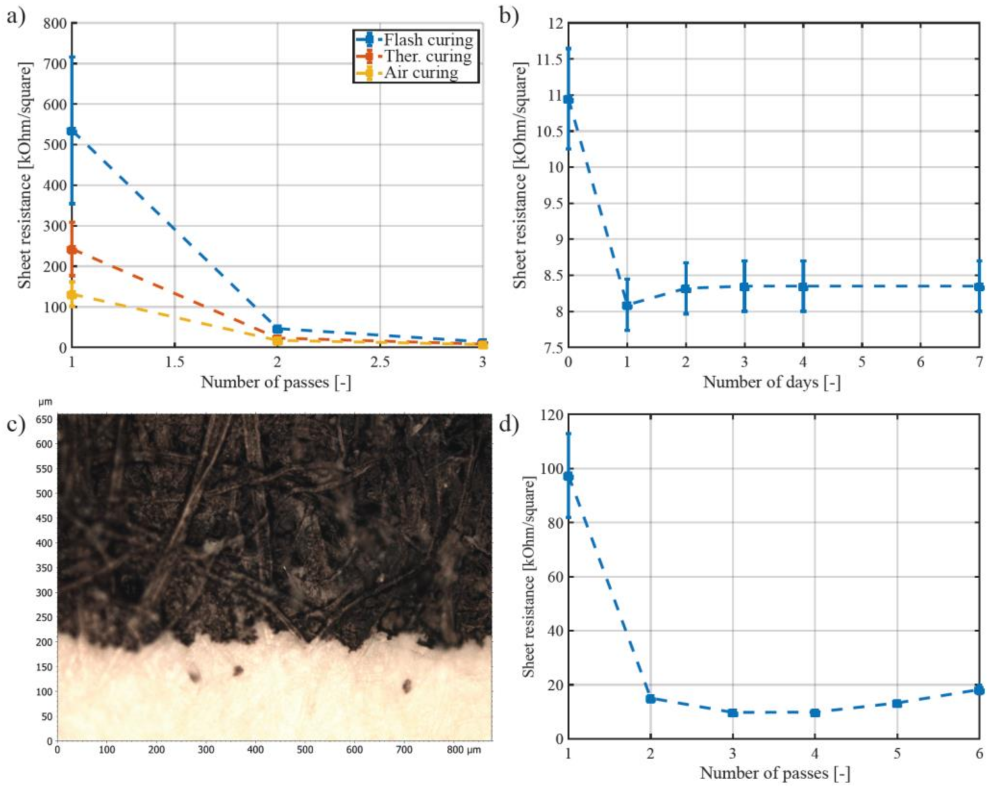
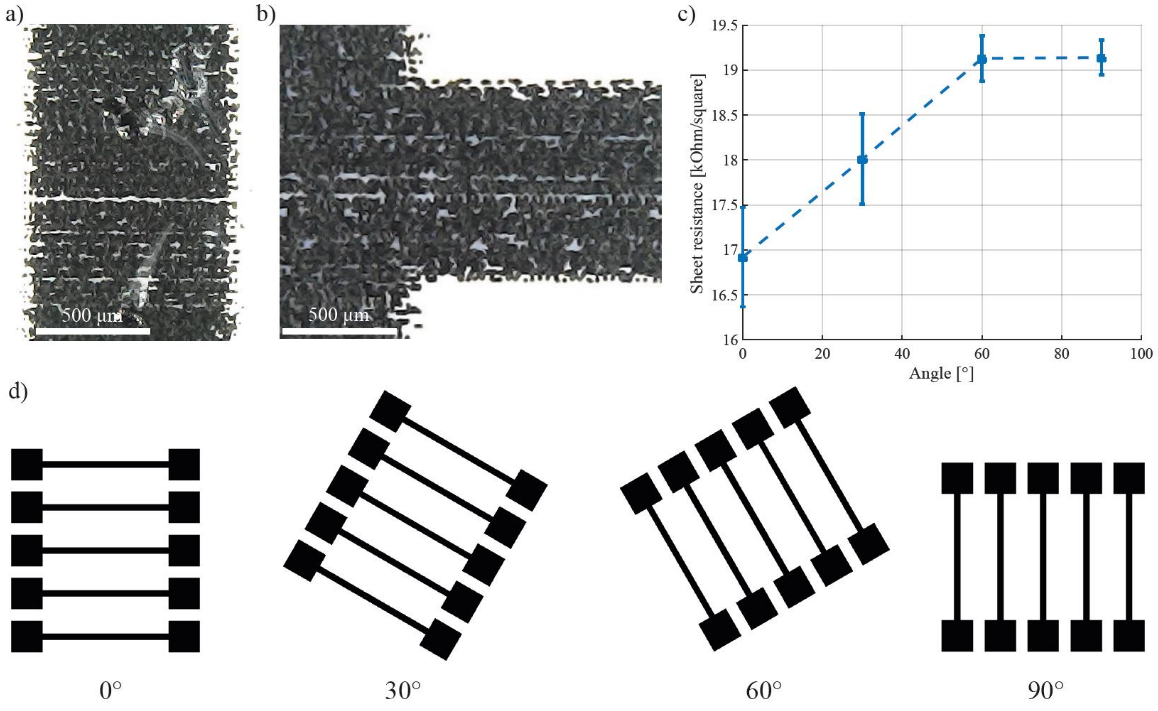
Research example – Incorporated Sensors

- Drone's sensing skin:
  - Investigating on the best printing properties for lowest resistivity





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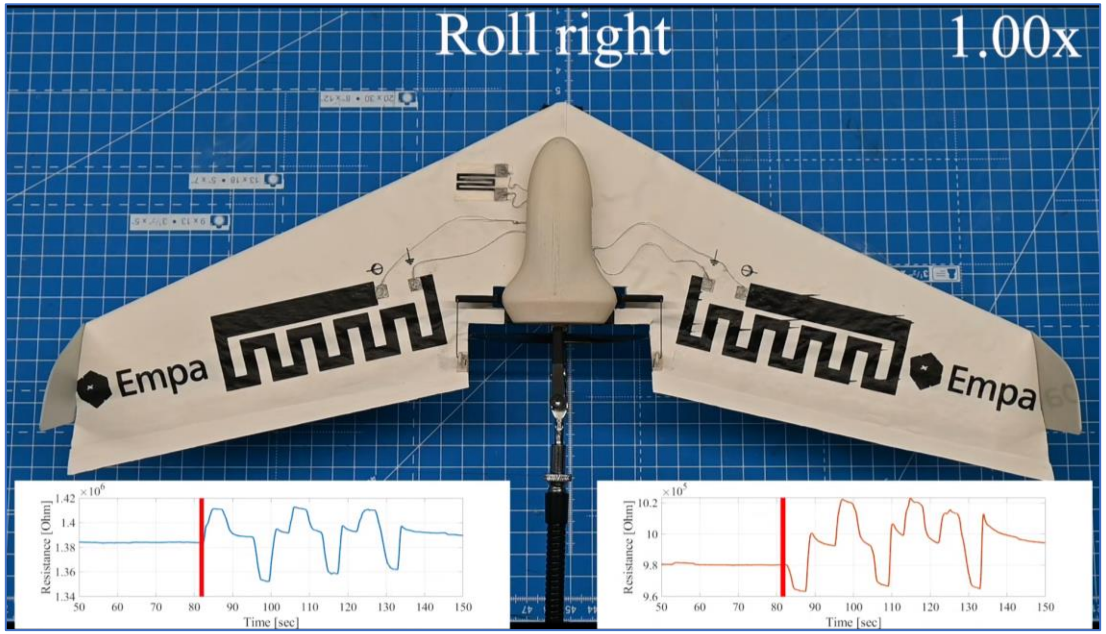
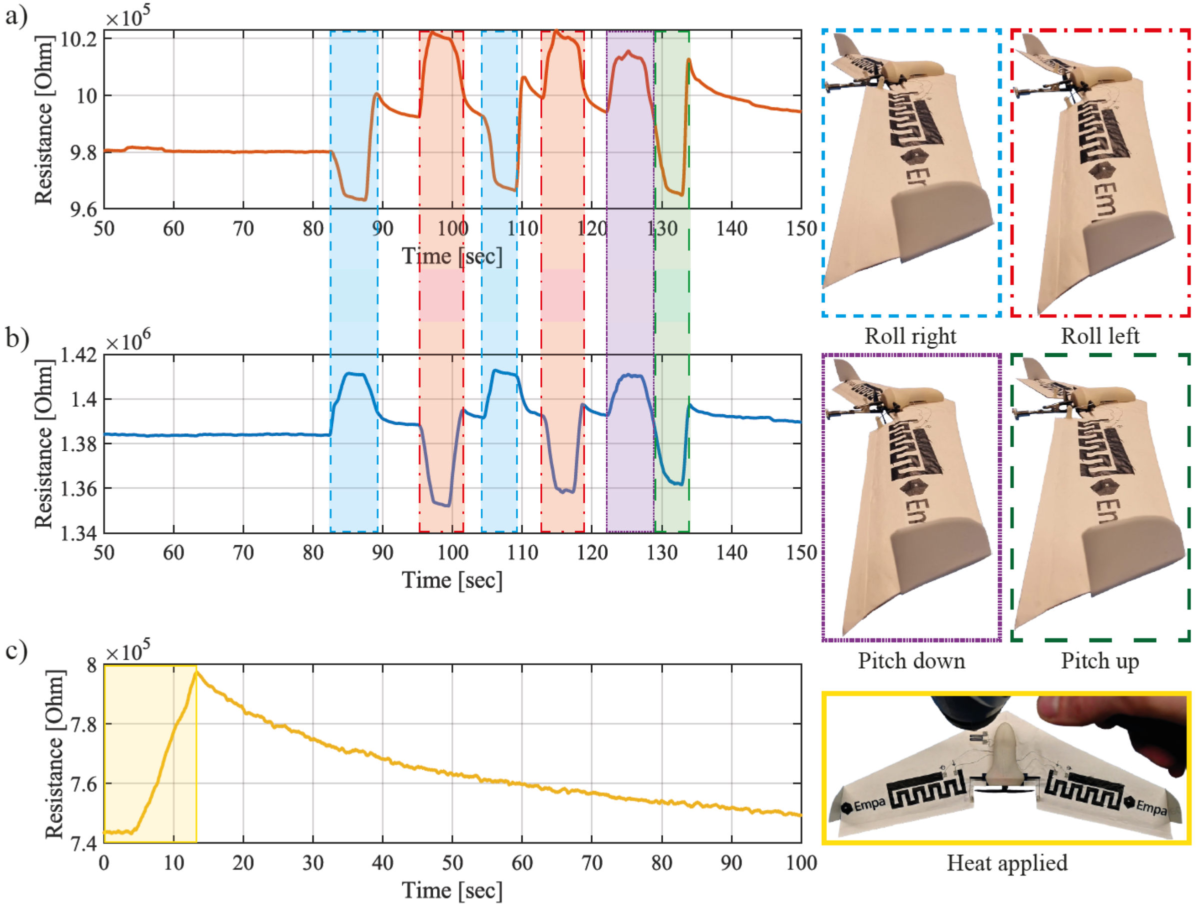
Research example – Incorporated Sensors

- Drone's sensing skin:
  - Integration of the sensing skin with the drone
  - Actuation and transmission of the changing resistivity values





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Biodegradable actuators

Image: Empa/ROK Architects

Biodegradable actuators – Materials

- Material Considerations:
  - Polymers from Renewable Sources:
    - Polylactic acid (PLA)
    - Polycaprolactone (PCL)
    - Polyhydroxyalkanoates (PHAs)

  - Cellulose-based materials:
    - Cellulose nanofibers
    - Bacterial cellulose

  - Protein-Based Materials:
    - Silk fibroin
    - Gelatin

  - Material Properties:
    - Biocompatibility (non-toxic and non-irritant)
    - Mechanical robustness during operational lifetime
    - Predictable and controllable degradation rate

Biodegradable actuators – Types & Fabrication

- Mechanisms of Actuation:
  - Humidity/Water-Responsive Actuators:
    - Materials that swell or contract with moisture changes
    - Example: Cellulose fibers that bend when exposed to humidity gradients
  - Thermoresponsive Actuators:
    - Thermal responsive materials
    - Shape memory polymers that revert to a “trained” shape at body or environmental temperature
  - Enzymatic or pH-Responsive Systems:
    - Materials engineered to degrade or change shape in response to biological conditions
  - “Passive” Systems:
    - Only some components of the actuator are biodegradable
- Fabrication Techniques:
  - Printing (screen printing, inkjet etc.) with biodegradable inks
  - Layer-by-layer assembly (coating etc.)
  - Electrospinning/Fiber Spinning

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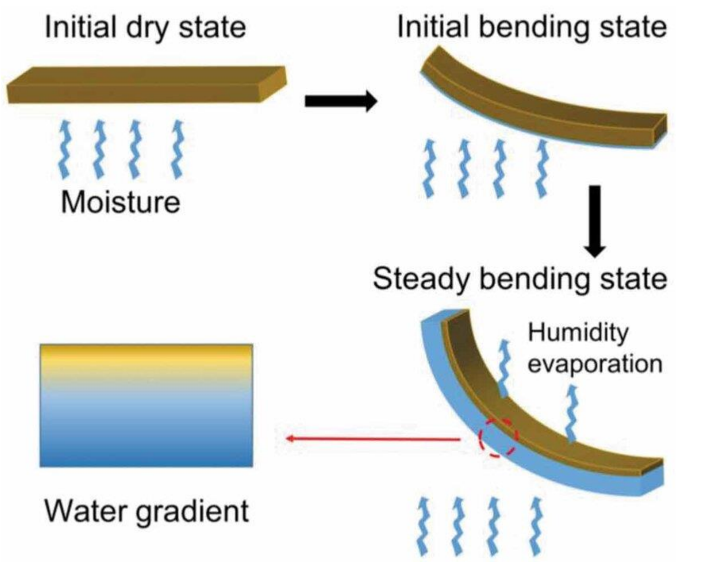
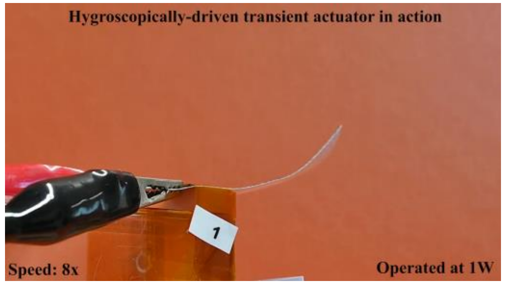
Biodegradable actuators – Considerations I

- Performance Challenges and Trade-Offs:
  - Design Challenges:
    - Balancing actuation strength and durability with controlled degradation
    - Ensuring uniform degradation profiles across complex structures
  - Material Limitations:
    - Limited force output compared to conventional actuators (metallic springs, motors)

Biodegradable actuators – Humidity/Water

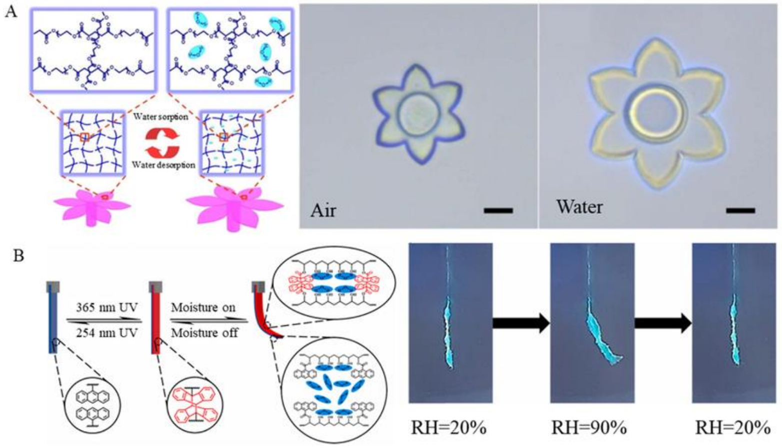
- Common Actuation Modes:
  - Swelling/Expansion: Increased volume or length upon water absorption.
  - Bending/Twisting: Asymmetric swelling across layers or fibers leads to directional movement.
  - Softening/Stiffness Changes: Material transitions from stiff to pliable state, enabling adaptive shapes.





- Cellulose-Based Materials:
  - Actuation Mechanism: Swelling of cellulose fibers upon moisture uptake leads to bending or twisting.
  - Advantages: Abundant, low-cost, naturally occurring, and easily degradable.

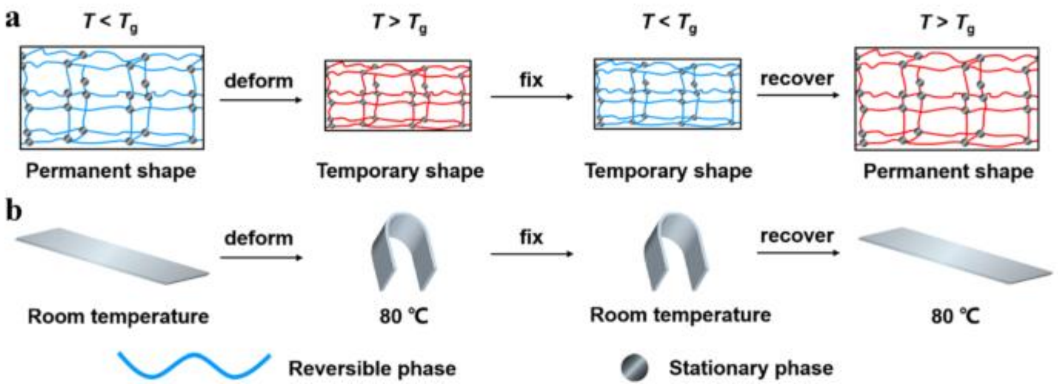
- Gelatin and Other Protein Hydrogels:
  - Actuation Mechanism: Hydrogels absorb water, expanding and softening, which can produce volumetric changes or shape transformations.
  - Advantages: Excellent biocompatibility, tunable mechanical properties, controllable biodegradation rates.



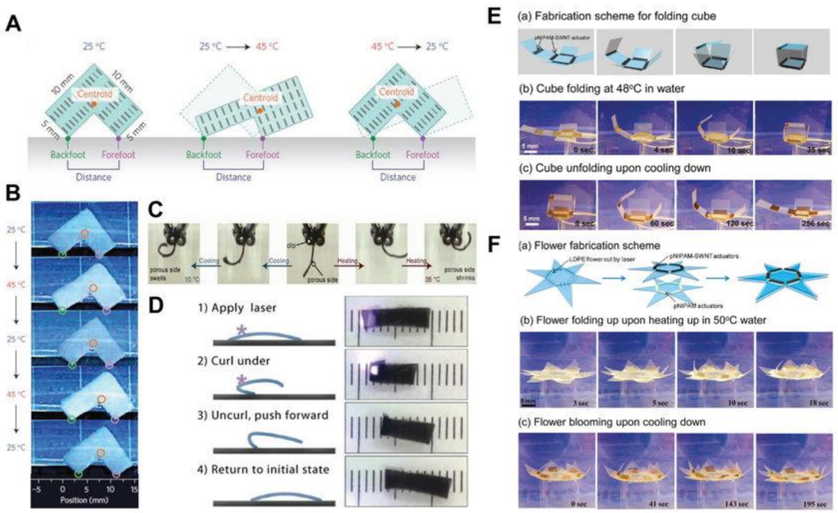
Source: [schema] https://www.researchgate.net/figure/A-schematic-of-a-moisture-based-actuation-in-our-cellulose-membranes_fig1_350702577; S. Mariani, et al., Mat. & Des., 2023; [17] M. Heinrich, et al., IEEE Robosoft, 2023; [14] F. Wiesemüller, IEEE Rob. Auto. Let., 2021 [hydrogel] URL: https://www.researchgate.net/figure/Hydrogel-actuators-in-response-to-humidity-stimuli-A-Schematic-illustration-of-the_fig2_368826794

Biodegradable actuators – Thermal

- Biodegradable Shape Memory Polymers (SMPs):
  - Examples: Poly(lactic acid) (PLA), Poly(caprolactone) (PCL)-based blends
  - Actuation Mechanism: These polymers are programmed into a temporary shape. Heating them to a specific transition temperature allows recovery of their original "memory" shape.
  - Advantages: Tailorable transition temperatures, established biodegradation profiles, and relatively straightforward fabrication.



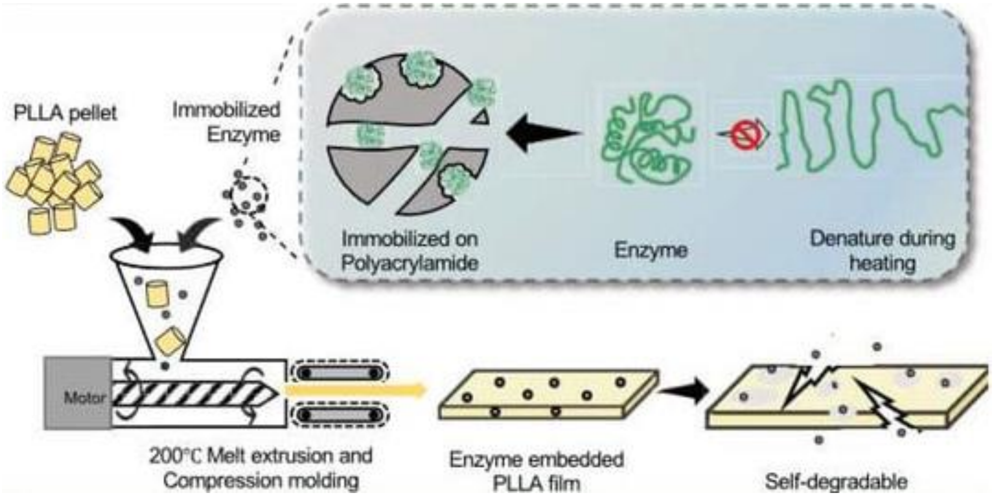
- Thermo-responsive Hydrogels (Biopolymer-Based):
  - Examples: Gelatin, Agarose blends
  - Actuation Mechanism: Gel-sol transitions and volume changes occur near characteristic transition temperatures. Heating leads to swelling, shrinking, or softening, enabling reversible shape alterations.
  - Advantages: Highly biocompatible, water-rich environment conducive to integrating cells or biomolecules, and natural degradation in biological settings.



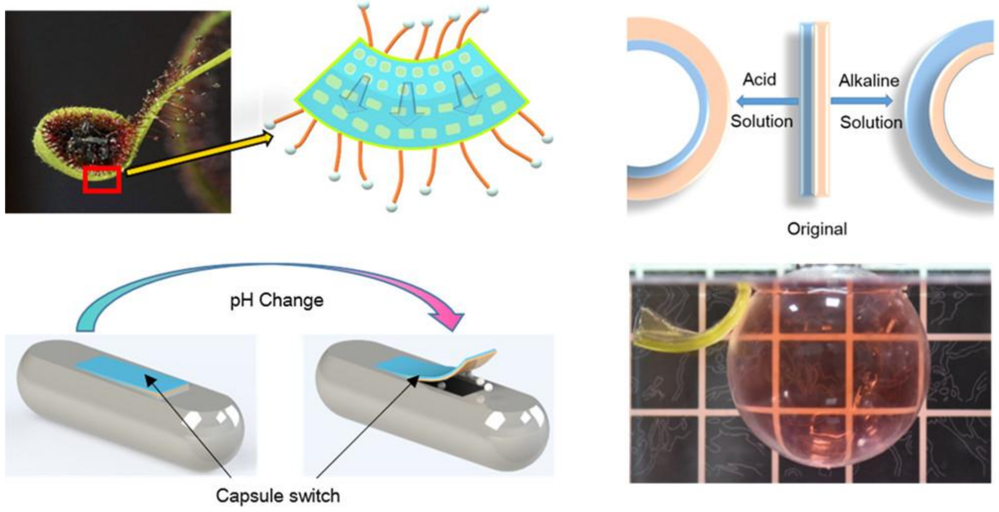
Source: [schema] URL: https://link.springer.com/article/10.1007/s42242-021-00151-6; [hydrogel] URL: https://www.researchgate.net/figure/Thermo-responsive-hydrogel-actuators-HAs-A-Basic-diagram-and-mechanism-for-a_fig2_326311901

Biodegradable actuators – Enzymatic/pH

- Enzyme-Degradable Polymers:
  - Examples: Silk fibroin modified with proteolytically degradable motifs, collagen-based materials
  - Actuation Mechanism: Specific enzymes (e.g., proteases) partially degrade the polymer matrix, altering mechanical properties and triggering motion or shape change.
  - Advantages: On-demand actuation in presence of target enzymes, ideal for biomedical environments such as implanted devices in living tissues.



- pH-Responsive Hydrogels:
  - Examples: Chitosan-based gels, alginate hydrogels, poly(lactic-co-glycolic acid) (PLGA) composites with pH-sensitive segments
  - Actuation Mechanism: Under acidic or basic conditions, the polymers swell, contract, or soften due to changes in polymer-ion interactions or charge distribution, enabling bending, expansion, or stiffening.
  - Advantages: Effective in biological fluids or environmental conditions with variable pH, allowing controllable, site-specific actuation and subsequent biodegradation.

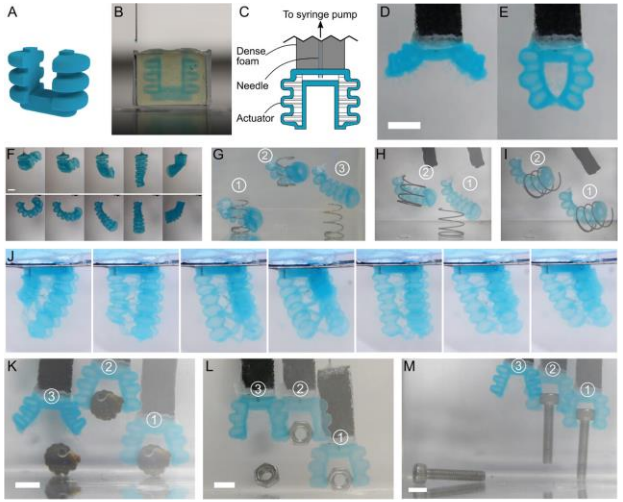


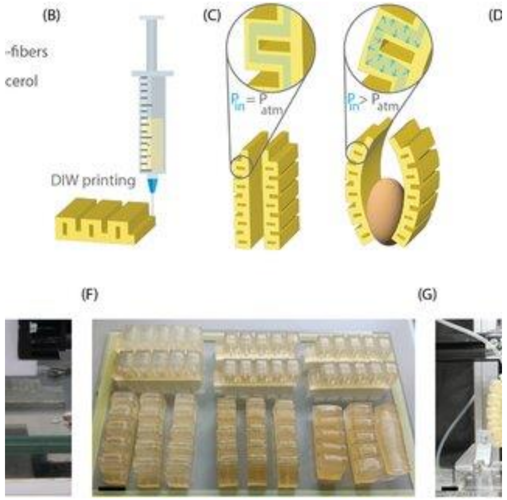
Source: [enzyme] URL: https://www.mdpi.com/2624-7402/5/1/6; [capsule] URL: https://pubs.acs.org/doi/10.1021/acsami.9b21713

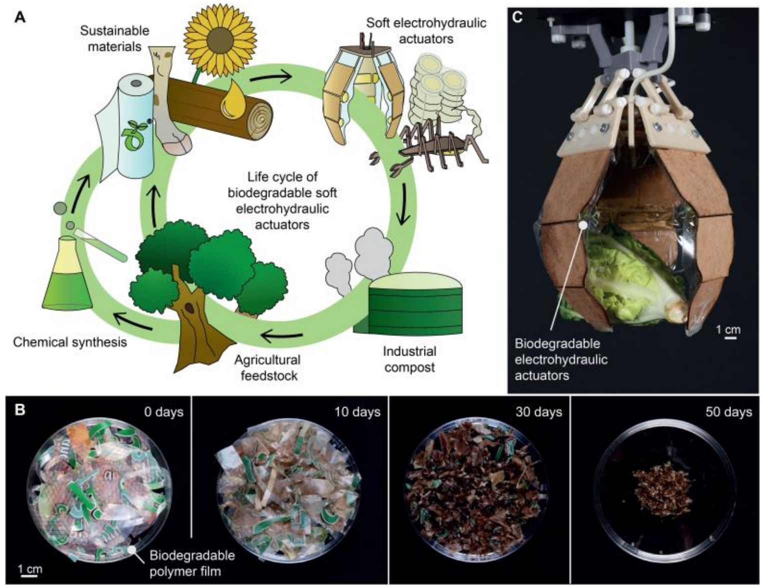
Biodegradable actuators – «Passive»

- Pneumatic systems for soft robotics:
  - Examples: Hydrogel actuators made for soft robotic gripping/manipulation tasks
  - Actuation Mechanism: Connecting a soft structure with an internal cavity to a pump and induce local deformation.
  - Advantages: Focus on gripper design and taking off-the-shelf components for inducing a pressure differential.

- Electrohydraulic systems:
  - Examples: Biaxially oriented polylactic acid (BOPLA)–based biodegradable gripper
  - Actuation Mechanism: HASEL (hydraulically amplified, self-healing, electrostatic) actuators as a class of soft actuators that feature direct electrical activation via Maxwell stress, electrical self-healing, and fast actuation.
  - Advantages: Focus on electrode design for fast actuation and not need to investigate on transient high-voltage electroncis.







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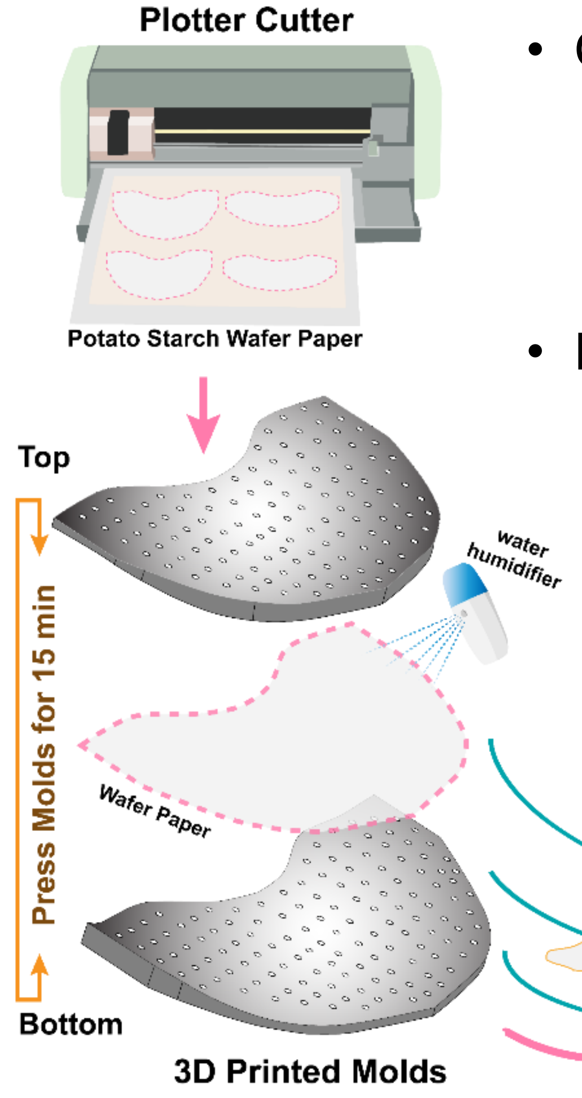
Comprehensive Results

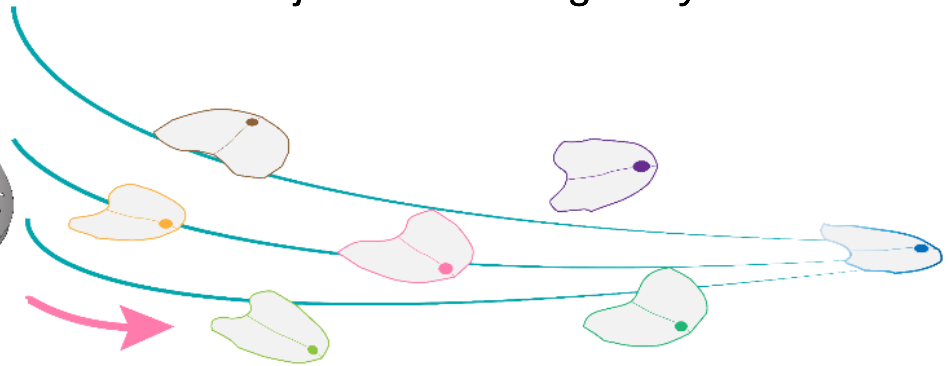
Image: Empa/SAM Architects/Filippo Bolognese

Acid Rain Monitoring

Source: [15] F. Wiesemüller, et al., Front. Rob. & AI, 2022

Acid Rain Monitoring





- Goal:
  - Design of a cheap manufacturing process for quick iterations
  - Use of biodegradable, non fossil based materials to enable one way missions

- Design:
  - Commercial potato starch paper was cut into the gliders shape
  - Template was wetted with water using a nebulizer
  - Paper was pressed with a 3D printed mould and dried for 10 minutes
  - Dummy mass was bonded to airframe to adjust centre of gravity

Source: [15] F. Wiesemüller, et al., Front. Rob. & AI, 2022

Images: Scott Zona

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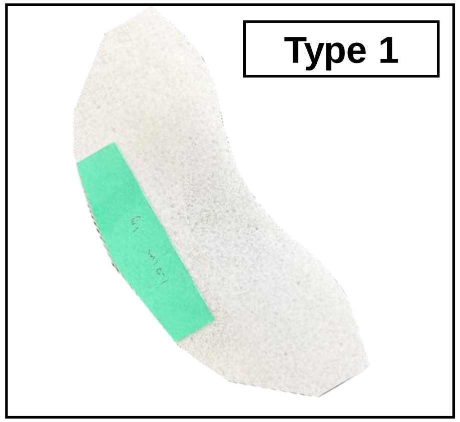
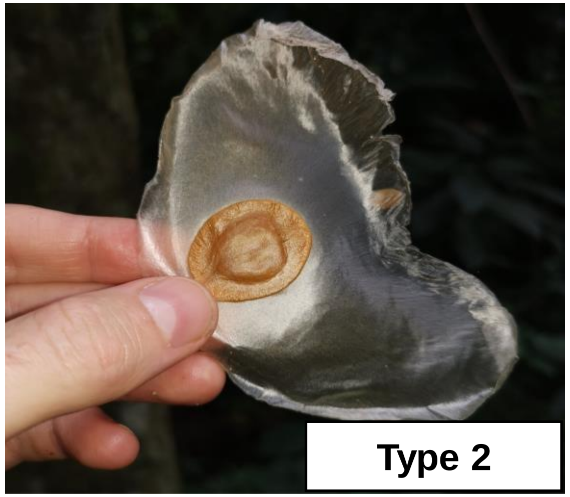
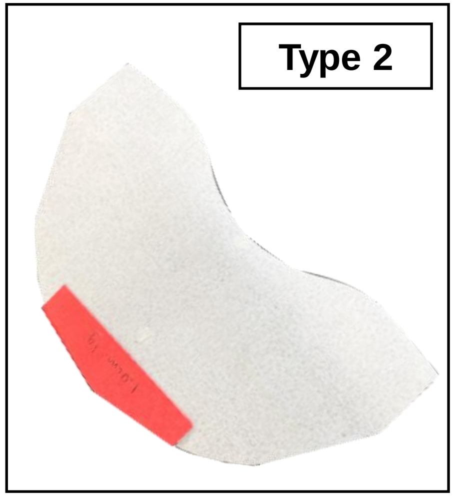
Acid Rain Monitoring

- Javan Cucumber (Alsomitra macrocarpa) seeds are excellent gliding seeds found in Southeast Asia, Australia and South America
- When ripe the seeds form angled back wings and reflexed airfoils, and are dispersed from their seedpod
- Javan Cucumber seed come in various shapes and sizes
- To cover the full design space two gliders with different aspect ratio were explored







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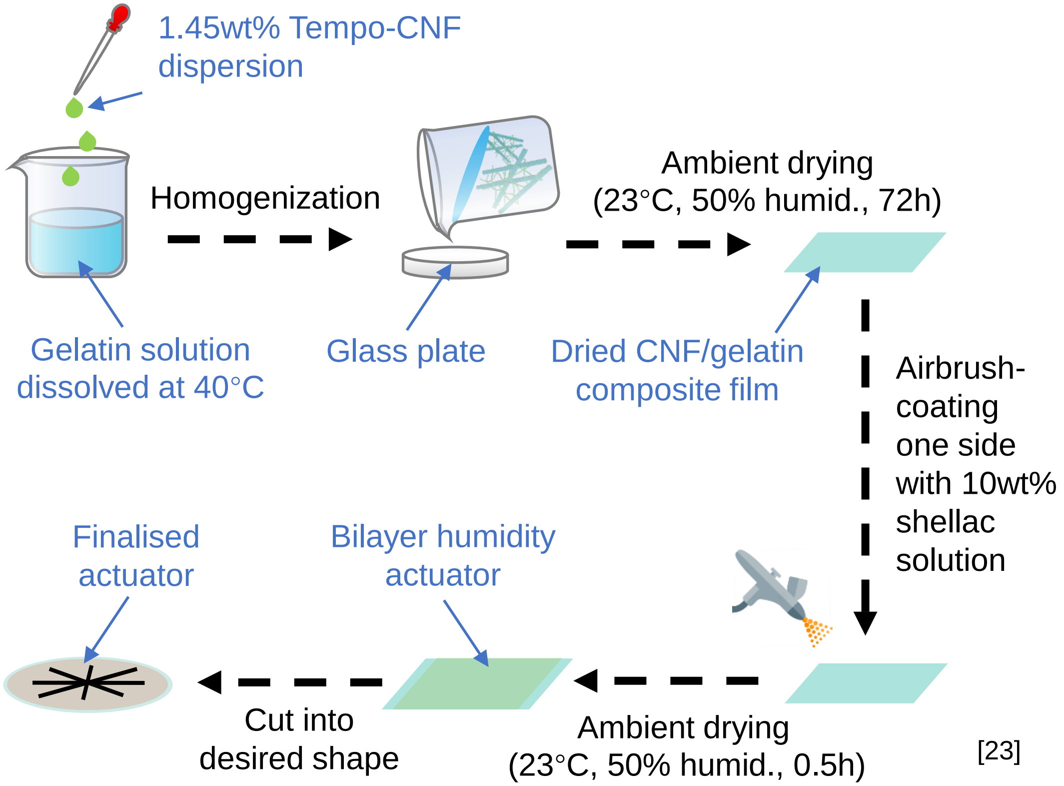
Acid Rain Monitoring



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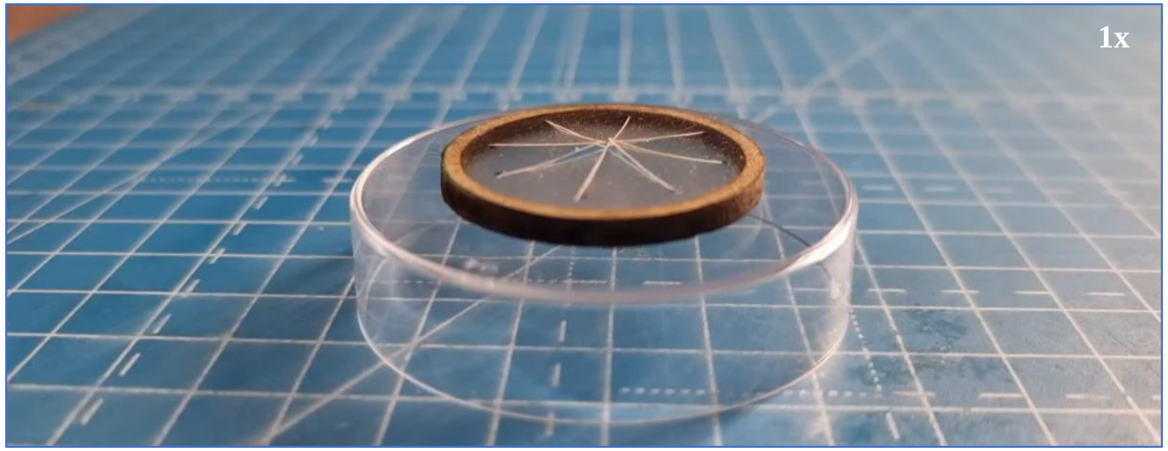

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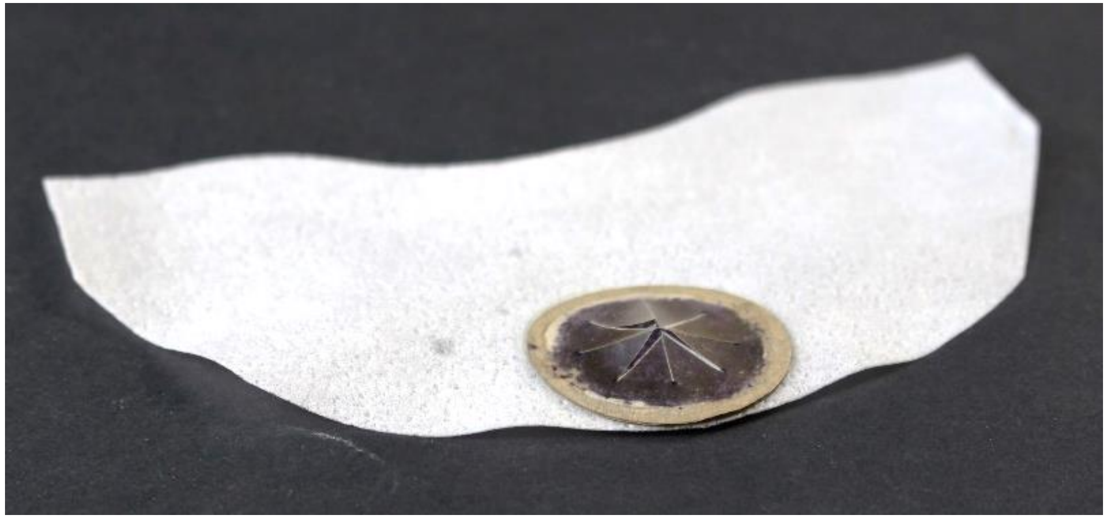
Acid Rain Monitoring



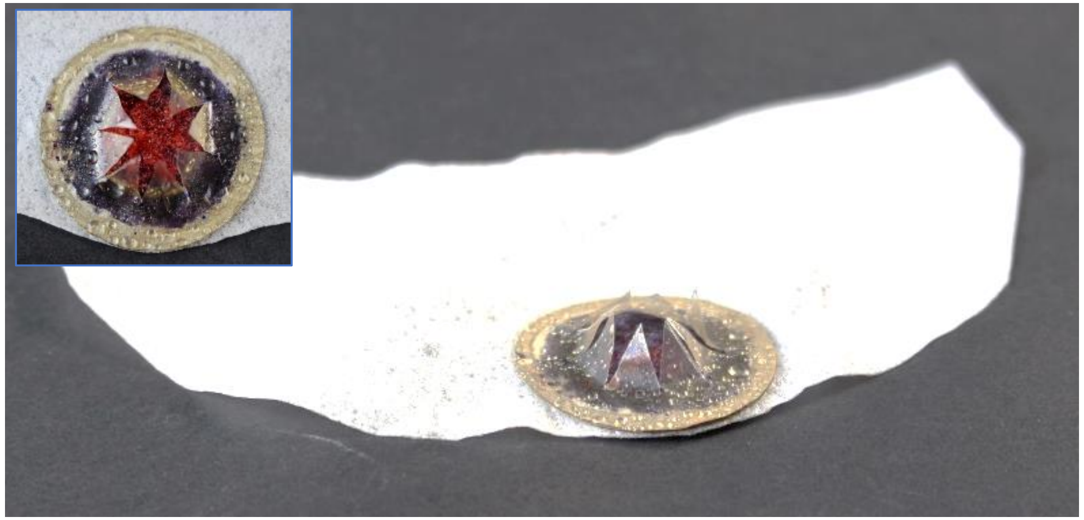
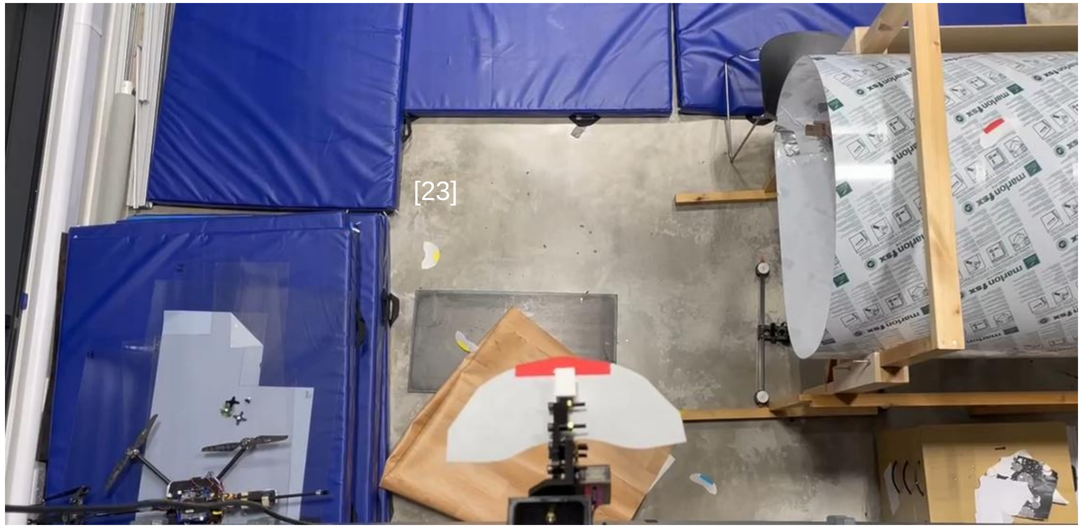


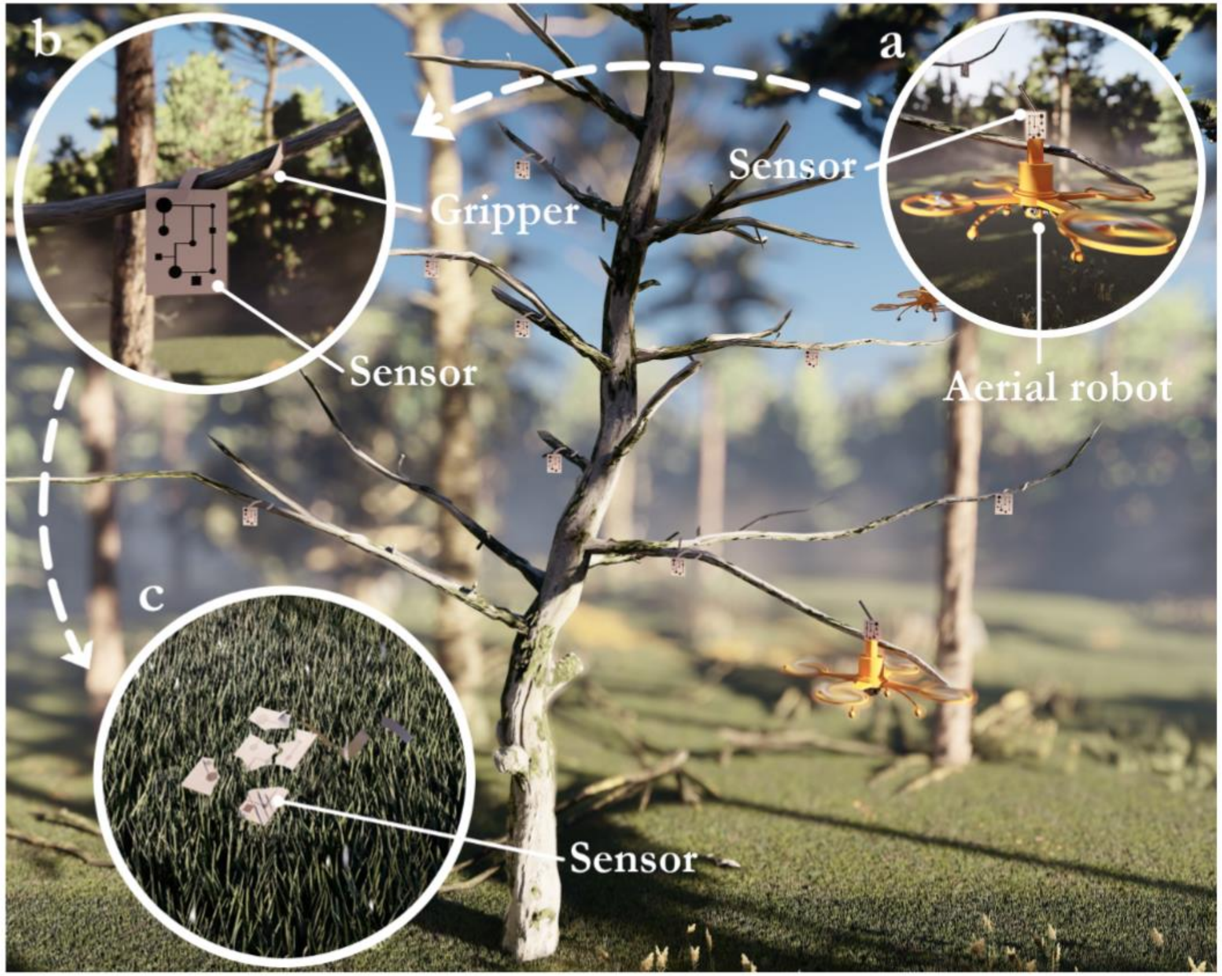
Image: Scott Zona



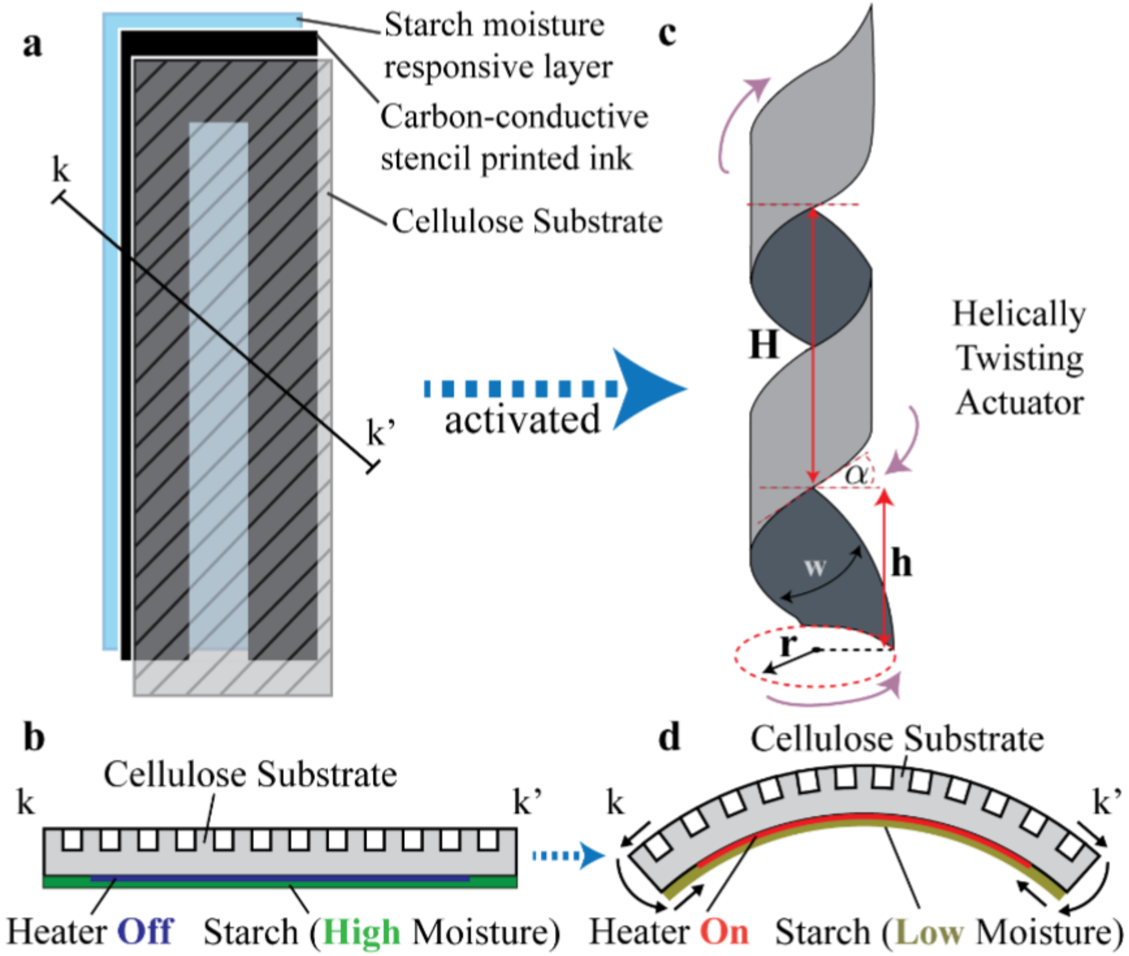
Source: [15] F. Wiesemüller, et al., Front. Rob. & AI, 2022

EPFL Empa

Biodegradable Sensor Deployment



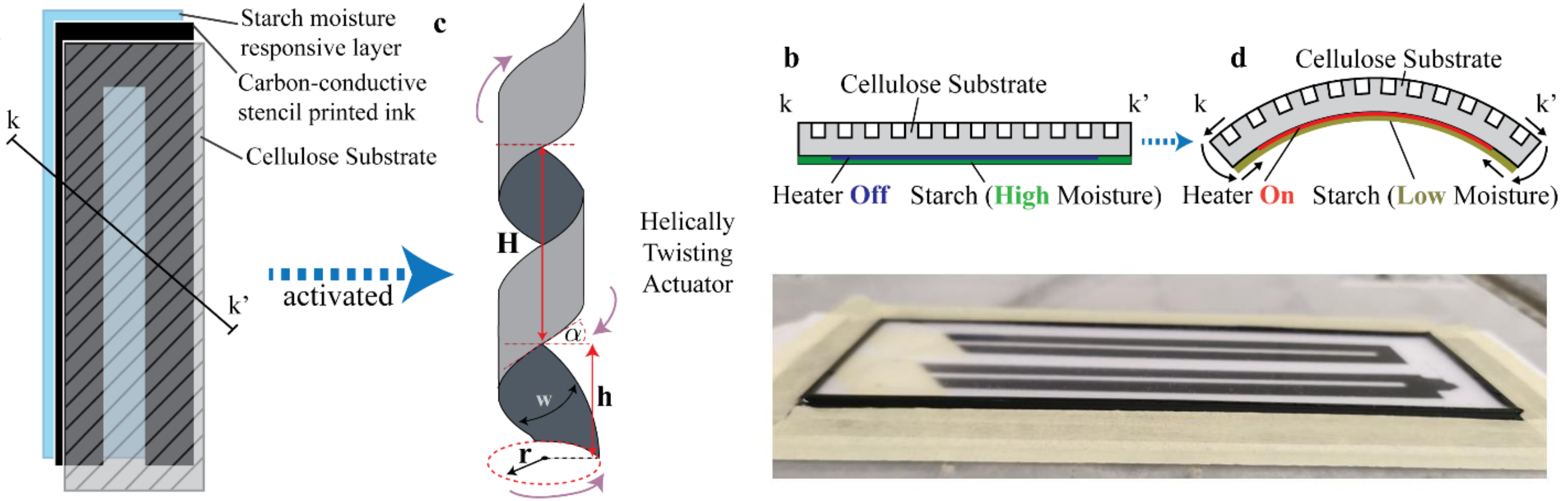
Rendering: Yusuf F. Kaya



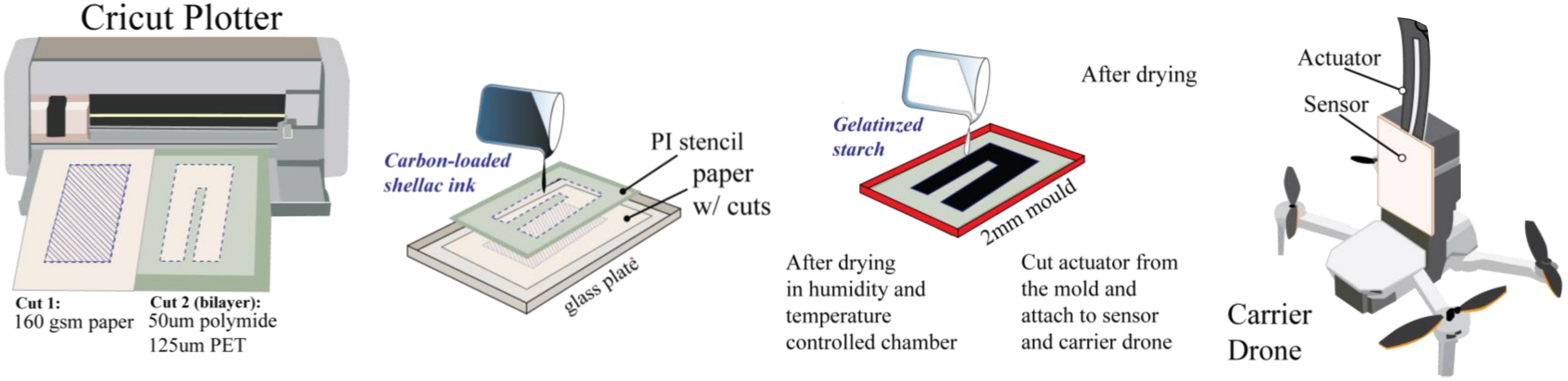
Source: [15] M. Heinrich*, F. Wiesemüller*, X. Aeby, Y.F. Kaya, D. Sivaraman, P.H. Nguyen, S. Song, G. Nyström, M. Kovač, "Hygroscopically-driven transient actuator for environmental sensor deployment," Robosoft, 2023.

Biodegradable Sensor Deployment

- Biodegradable, non-toxic and mostly renewable materials
- Tri-layer architecture:
  - Hygroscopically active layer experiencing shrinkage (starch)
  - Passive, anisotropic layer for structural support (paper)
  - Joule-heating element for inducing shrinkage (carbon ink)

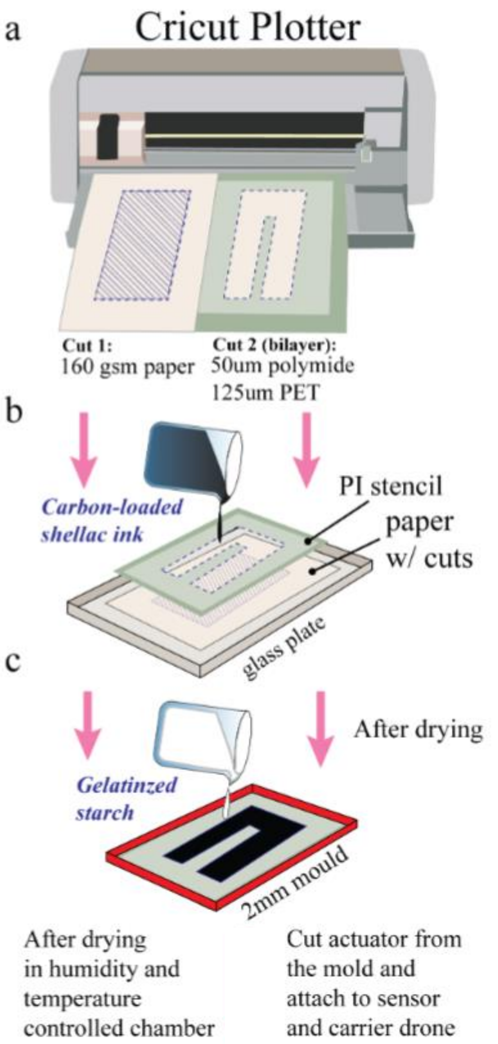


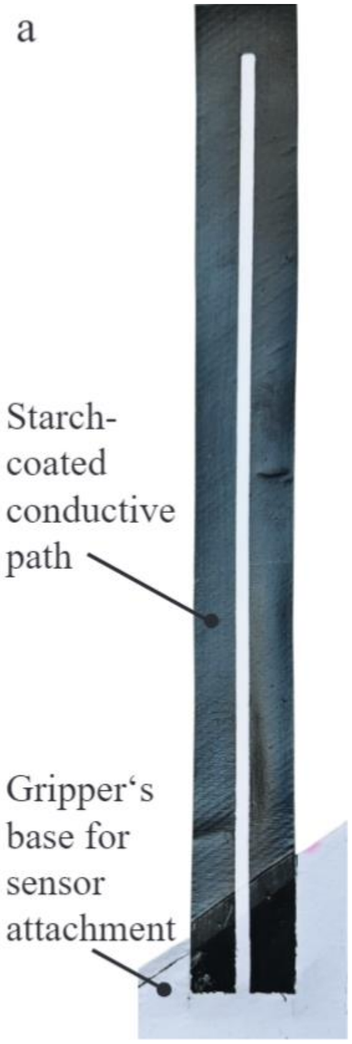
- Cuts to tailor substrate stiffness → anisotropy for coiling behavior
- Printed conductive heater → loss of free/unbounded moisture induces shrinkage
- Micro-cracks due to heating → non-reversible coiling

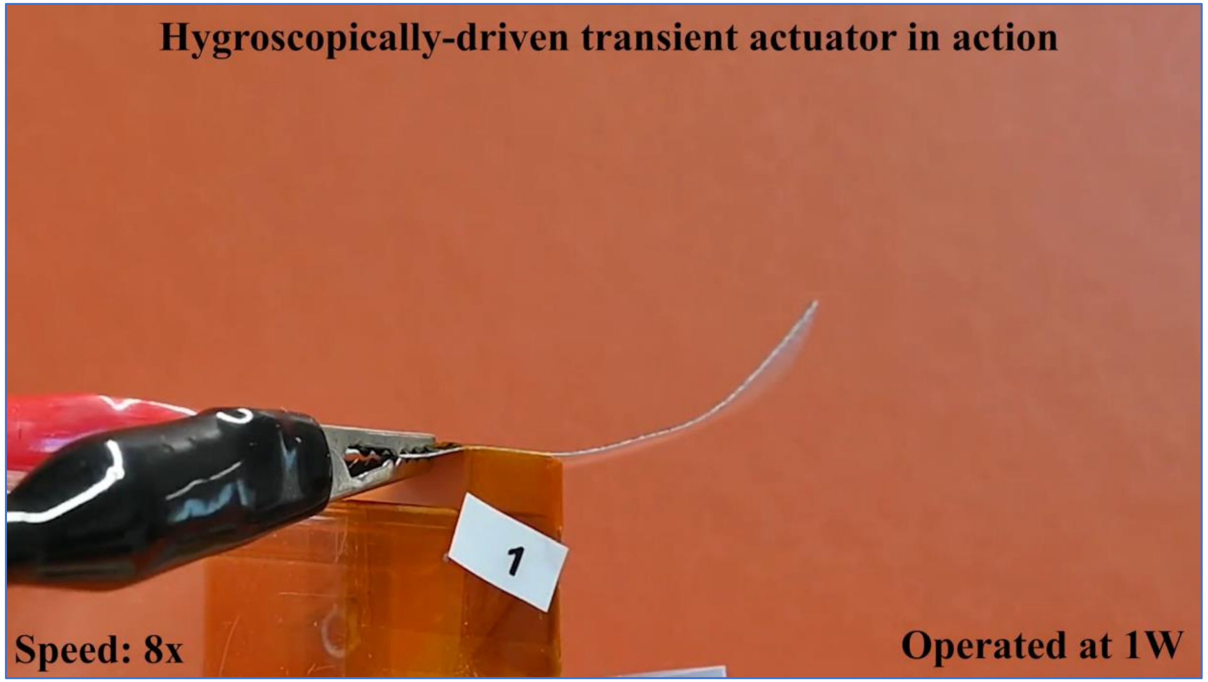


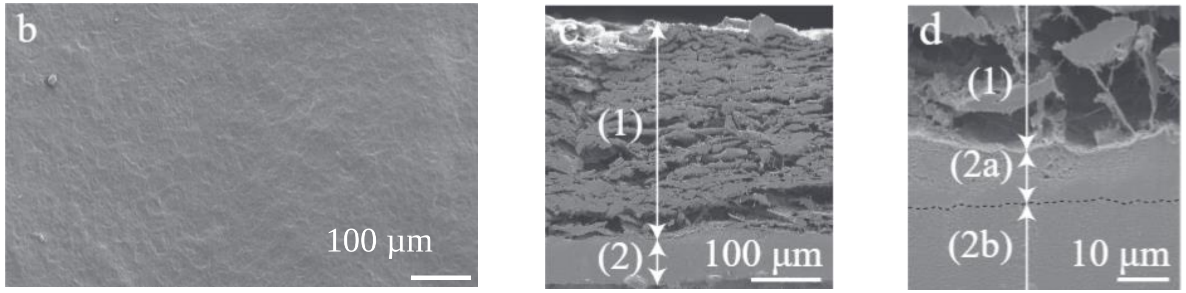
Source: [15] M. Heinrich*, F. Wiesemüller*, X. Aeby, Y.F. Kaya, D. Sivaraman, P.H. Nguyen, S. Song, G. Nyström, M. Kovač, "Hygroscopically-driven transient actuator for environmental sensor deployment," Robosoft, 2023.

Biodegradable Sensor Deployment









Top view
[starch]

Side view
[paper (1), coating (2)]

Side view
[ink (2a), starch (2b)]

Source: [15] M. Heinrich*, F. Wiesemüller*, X. Aeby, Y.F. Kaya, D. Sivaraman, P.H. Nguyen, S. Song, G. Nyström, M. Kovač, "Hygroscopically-driven transient actuator for environmental sensor deployment," Robosoft, 2023.

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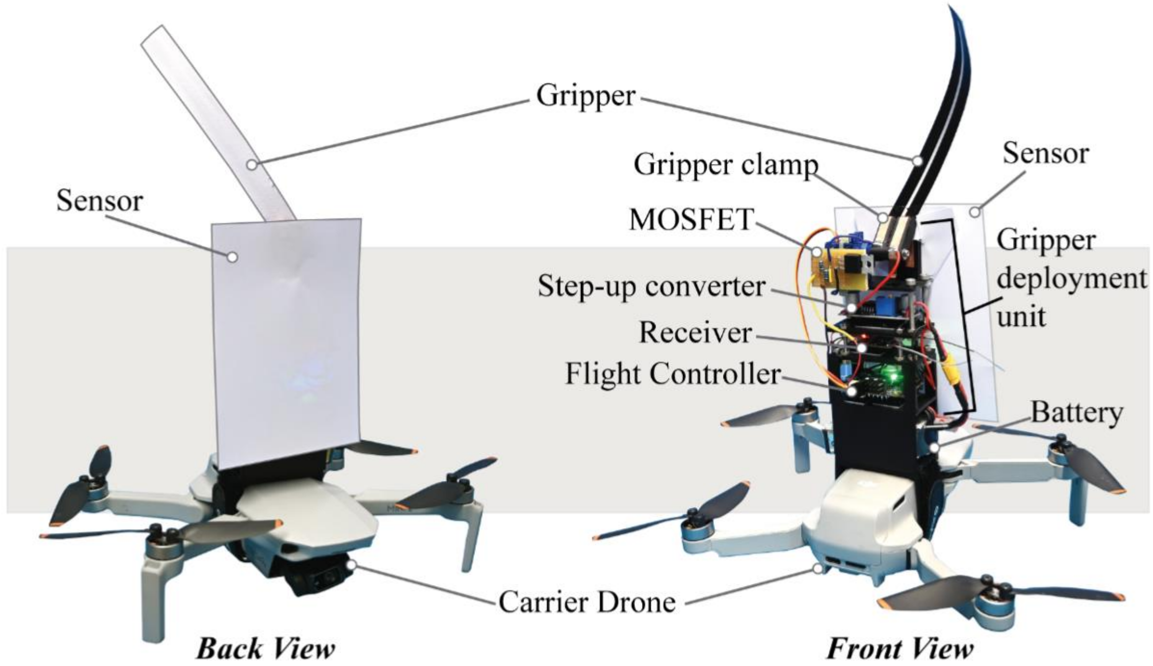
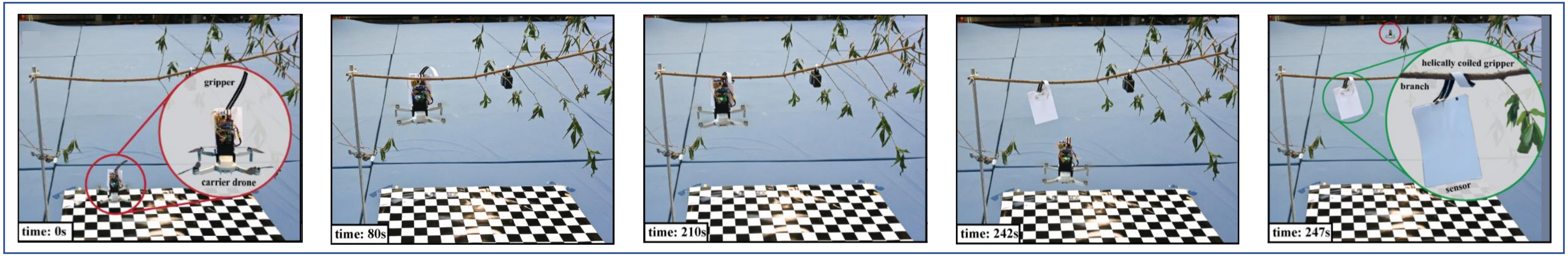
Biodegradable Sensor Deployment





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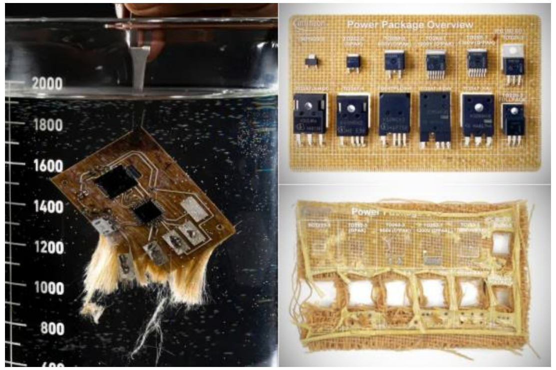
Source: [15] M. Heinrich*, F. Wiesemüller*, X. Aeby, Y.F. Kaya, D. Sivaraman, P.H. Nguyen, S. Song, G. Nyström, M. Kovač, "Hygroscopically-driven transient actuator for environmental sensor deployment," Robosoft, 2023.

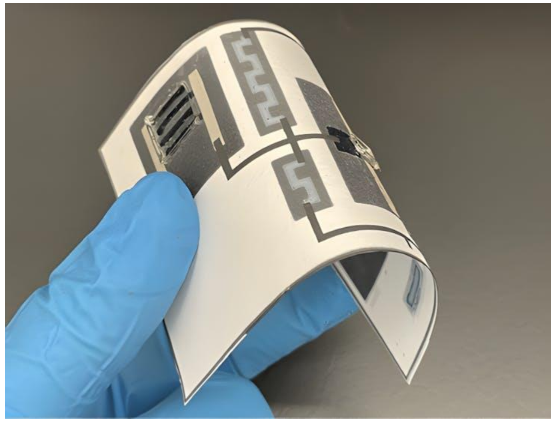
Challenges – Technical

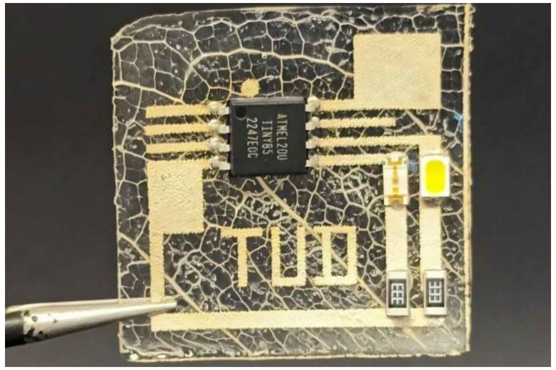
- **Limitations in Material Properties:**
  - High conductivity materials are often not biodegradable.
  - Biodegradable materials typically have lower mechanical strength, flexibility, or electrical performance.
  - Limited availability of biodegradable alternatives for critical components.

- **Non (fully) degradable Electronics:**
  - Sensors and actuators often rely on regular, non-degradable components.
  - Power systems (e.g., batteries, circuits) lack biodegradable options with sufficient energy density.

- **Environmental Stability:**
  - Biodegradable materials can degrade prematurely in humid or extreme conditions.
  - Sensitivity to environmental factors (e.g., temperature, moisture) impacts long-term use.







Source: [dissolvingpcb] URL: https://www.techeblog.com/infineon-biodegradable-circuit-boards-dissolve-water-jiva-materials/, [paper] URL: https://www.hackster.io/news/integrated-papertronics-offers-single-use-electronic-circuit-boards-made-entirely-of-paper-987a15855a3d; [leaf] URL: https://www.greenmemag.com/science-technology/how-a-simple-leaf-could-transform-the-future-of-electronics/

Challenges – Design Trade-Offs

- **Biodegradability vs. Signal Consistency:**
  - Conductive materials often exhibit inconsistent signals over time.
  - Long-term signal degradation due to environmental exposure.
- **Biodegradability vs. Robustness:**
  - Trade-off between making materials biodegradable and ensuring durability.
  - Compromises in physical robustness to enable eco-friendly degradation.
- **Balancing Complexity:**
  - Complex systems require advanced electronics (biodegradable and non-biodegradable), which generally cannot be biodegradable.

Challenges – Real-World Adaptation

- **Limited Field Testing:**
  - Most biodegradable robots are tested in controlled environments, not real-world scenarios.
  - Lack of data on performance under harsh, dynamic conditions

- **Adaptation to Specific Applications:**
  - Insufficient customization for unique use cases.
  - Need for interdisciplinary collaboration to address specific challenges.

- **Validation of Biodegradation:**
  - Unclear degradation timelines and environmental impact assessments.
  - Testing in diverse ecosystems to confirm safe and complete biodegradation.

Outlook – Biodegradable vs. sustainable

- **Lack of Life Cycle Assessments (LCA):**
  - Biodegradable robots are often designed with a focus on their end-of-life degradation, neglecting the environmental impacts of material sourcing, manufacturing, and disposal processes.
  - Sustainable robots, in contrast, emphasize a cradle-to-grave or cradle-to-cradle design that considers the entire lifecycle.

- **Focus on Degradability vs. Broader Environmental Impact:**
  - Biodegradable robots prioritize material degradation but may rely on energy-intensive production or non-renewable resources.
  - Sustainable designs aim to minimize overall carbon footprint, resource use, and environmental harm.

Outlook – Biodegradable vs. sustainable

- **Integration of Renewable Energy and Recyclability:**
  - Sustainable robots often incorporate renewable energy sources (e.g., solar panels) and recyclable components.
  - Biodegradable robots currently lack such integration, focusing solely on degradation.

- **The Need for Combined Approaches:**
  - Future designs should integrate biodegradability with sustainability by:
    - Using LCAs to identify and mitigate environmental hotspots.
    - Employing renewable materials and clean manufacturing processes.
    - Balancing material choices with long-term energy efficiency and recyclability.

Outlook – Further Impact

Structures
Soft elastomeric materials

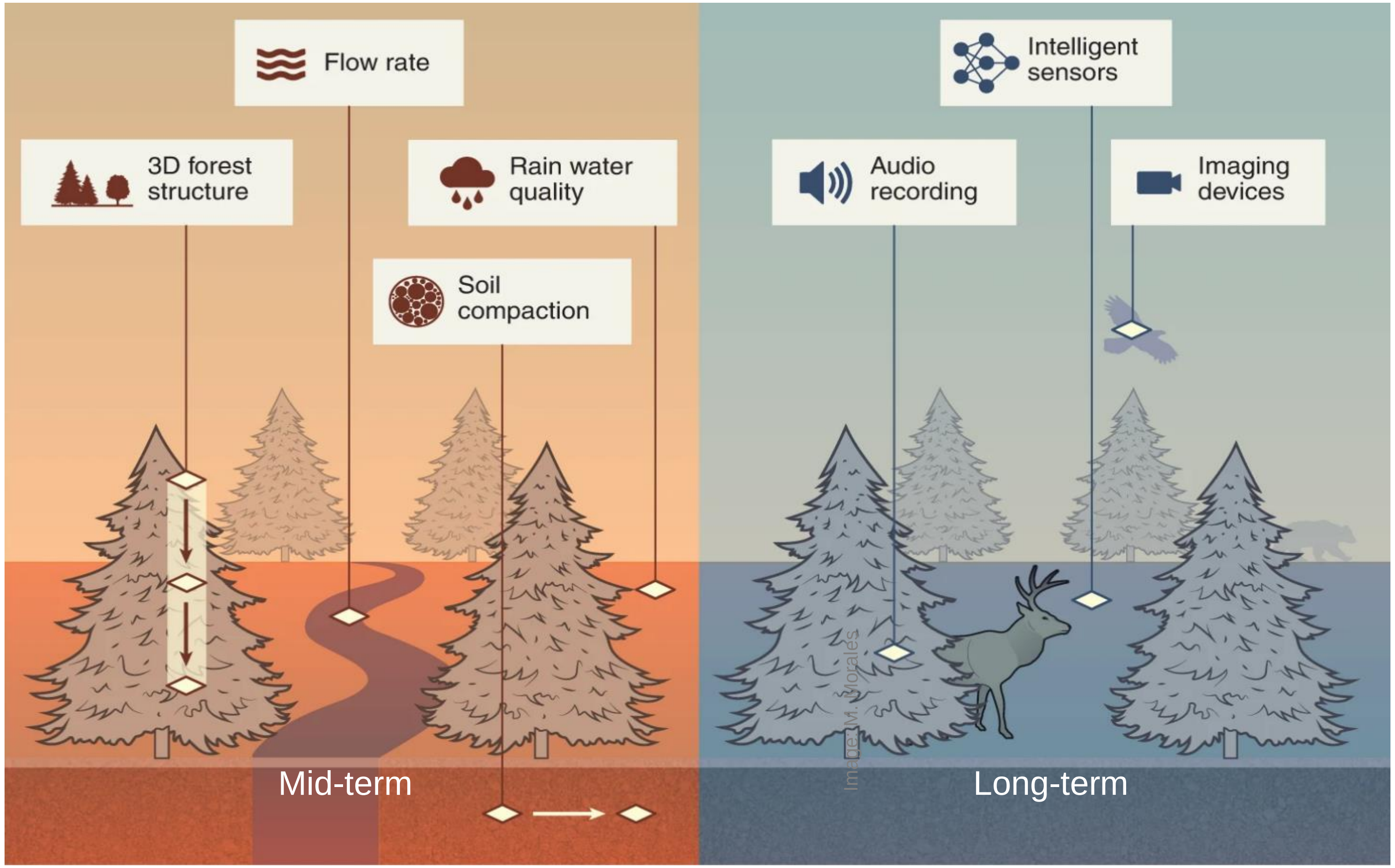
Electronics
Computational units
Higher energy density power sources
High conductivity inks (e.g. for antennas)

Platforms
Other types of locomotion
(e.g. swimming transient robots)

Bio-hybrid systems
Self-healing/reinforcing
Sensors and actuators
Microbial fuel cells

Field testing
Close collaboration with environmentalists
Continuous improvement

ENABLING THE FULL POTENTIAL



Further reading

Books:
Hwang Suk-Won, Rogers A. John. Materials and Integration Approaches for Transient Electronic Systems: High Performance Silicon-based Biodegradable/Biocompatible Electronics. Scholars' Press [2014] URL: https://www.amazon.com/Materials-Integration-Approaches-Transient-Electronic/dp/3639701925

Gomaa A. M. Ali, Abdel Salam H. Makhlouf. Handbook of Biodegradable Materials. Springer [Feb. 2023] URL: https://link.springer.com/referencework/10.1007/978-3-031-09710-2

Alhanish Atika., Gomaa A. M. Ali. Biodegradable Polymers. Springer [Nov. 2022] https://link.springer.com/referenceworkentry/10.1007/978-3-030-83783-9_13-1

Online resources:
Materiom Website, URL: https://resources.materiom.org/

Q&A & Feedback

Open questions?

For more information visit:
robotics.empa.ch