EM&Ts INTEGRATION CARDS

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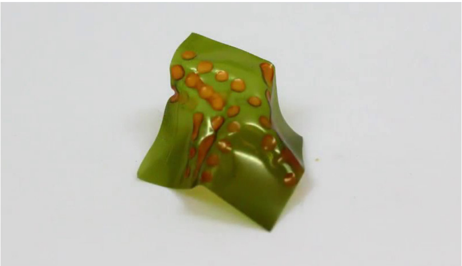
1.2. Integrating bioresponsiveness

Biological organisms can be used as **bio-sensors** and **bio-actutors**. The bioprinting process embeds the organism within predetermined scaffolds allowing the organisms to take form during its lifecycle.

- ⊕ Alternative sensors/actuators
- ⊕ Less electronics in interactive systems
- ⊖ Short-lasting life
- ⊖ Challenging in application



Organic primitives

By MIT and Primitives, Viirj Kan

It uses **bioplastic** products with **advanced sensing**, display, and biodegradation properties, like a pH-reactive color-changing material.

https://primitives.io

BioLogic

By MIT

"Animated cells" using Natto **bacteria** to respond to moisture with shape-shifting behaviour and to potentially provide **light-emitting behaviour**.

https://tangible.media.mit.edu/project/biologic/

References

Organic Primitives: Synthesis and Design of pH-Reactive Materials using Molecular I/O for Sensing, Actuation, and Interaction. Kan et al. CHI 2017.

BioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. Yao et al. CHI 2015.

Living electrodes based on green algae in hydrogels. Al-Mossawi et al. Material Advances, 2021.

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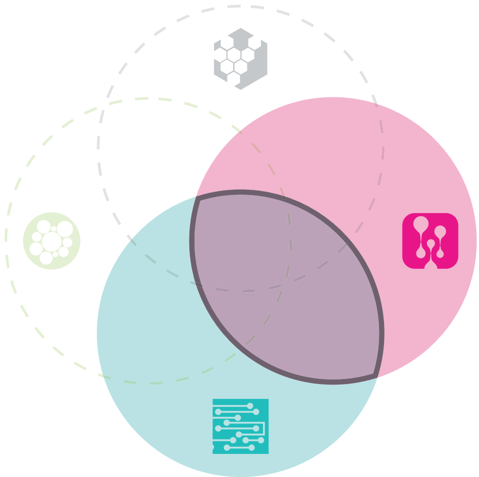
ADVANCED GROWING ICS MATERIALS

2-AREAS INTEGRATION

INTEGRATION

1. ADVANCED GROWING ICS MATERIALS



One **challenge** for the development of interactive systems is **sustainability**, particularly by using non-toxic, renewable and biodegradable materials.

Some researchers and designers are working in this direction, combining interactive, connected and smart (ICS) materials with grown biomaterials (e.g. mycelium, bacteria cellulose) or **replacing electronic components with biosensors and bioactuators** (e.g. pH sensitive bacteria).

(Cover) BioLogic by MIT, detail of sweat-reactive sportswear; (1) Organic primitives by MIT, samples of pH-reactive bioplastic; (2) Living electrodes based on green algae, proof of concept; (3) DIY electronics with mycelium by Lazaro Vasquez, Vega, basic example of led-button-battery circuit on a mycelium board.

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1.1. Mycelium-based electronics and wearables

The design process used at the Interactive Organism Lab coordinated by Katia Vega at UCL focuses on exploring sustainable **interactive** objects and **wearables using mycelium** - and organic grown material – combined with interactive technologies.

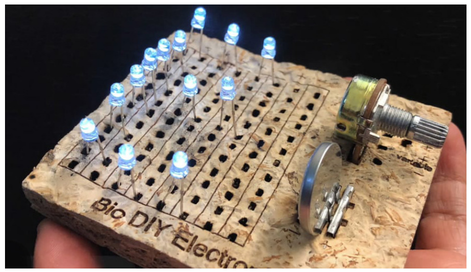
- ⊕ Thermal resistance
- ⊕ Partially compostable
- ⊕ Reusable Electronics
- ⊕ Highly renewable
- ⊖ Low water resistance
- ⊖ Low weathering resistance

Myco Accessories

By E. Lazaro Vasquez, K. Vega

Jewelry using lamination technique to **embed electronics** into mycelium as a compostable material.

http://www.eldylazaro.com/portfolio/myco-accessories/



DIY Electronics with Mycelium

By E. Lazaro Vasquez, K. Vega

Mycelium composites with common **digital fabrication techniques** to replace plastic in electronics for fast prototyping.

www.eldylazaro.com/portfolio/diy-electronics-with-mycelium/

References

From plastic to biomaterials: prototyping DIY electronics with mycelium. Lazaro Vasquez, Vega. 2019.

Myco-accessories: Sustainable wearables with biodegradable materials. Lazaro Vasquez, Vega. ISWC 2019.

OPPORTUNITY

2.2. Monitoring wearables for healthcare

Wearable monitoring systems allow physiological signals to be **continuously monitored** during normal daily activities. This can overcome the problem of infrequent clinical visits that can only provide a brief window into the physiological status of the patient. (e.g., wireless-enabled garment with embedded textile sensors for simultaneous acquisition and continuous monitoring of **ECG**, **respiration**, **EMG** and physical activity)

- ⊕ Massive expected market growth
- ⊕ Real-time
- ⊕ Non-invasive

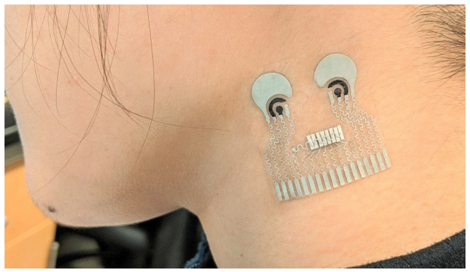
- ⊖ Requires personal calibration
- ⊖ Lack of self-calibration protocols
- ⊖ Size
- ⊖ Energy consumption

CareTaker Medical Wearable

By Patientcaresolution

It uses a finger cuff to measure accurately a whole range of **physiological parameters**, like beat-by-beat blood pressure and heart rate.

https://www.patientcaresolutions.eu/products/medical-wearables.html



Skin patch health monitor

By UC San Diego

Soft, stretchy skin patch wearable on the neck to continuously track blood pressure and heart rate, but also levels of **glucose, lactate, alcohol, or caffeine**.

https://statnano.com/news/68713/

References

Stretchable Carbon and Silver Inks for Wearable Applications. Claypole et al. Nanomaterials, 2021.

Recent Advances in Nanomaterial-Enabled Wearable Sensors: Material Synthesis, Sensor Design, and Personal Health Monitoring. Peng et al. Small, 2020.

Evolution of Wearable Devices with Real-Time Disease Monitoring for Personalized Healthcare. Guk et al. Nanomaterials (Basel), 2019.

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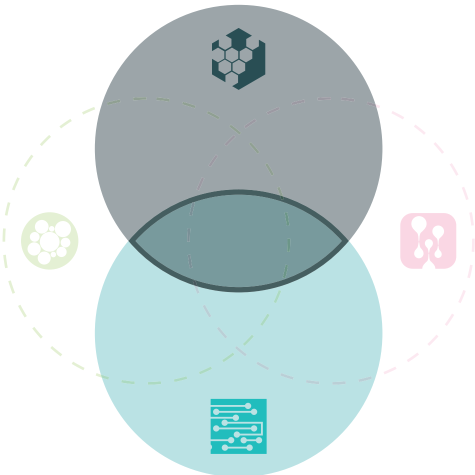
NANO-ICS MATERIALS

2-AREAS INTEGRATION

2. NANO-ICS MATERIALS

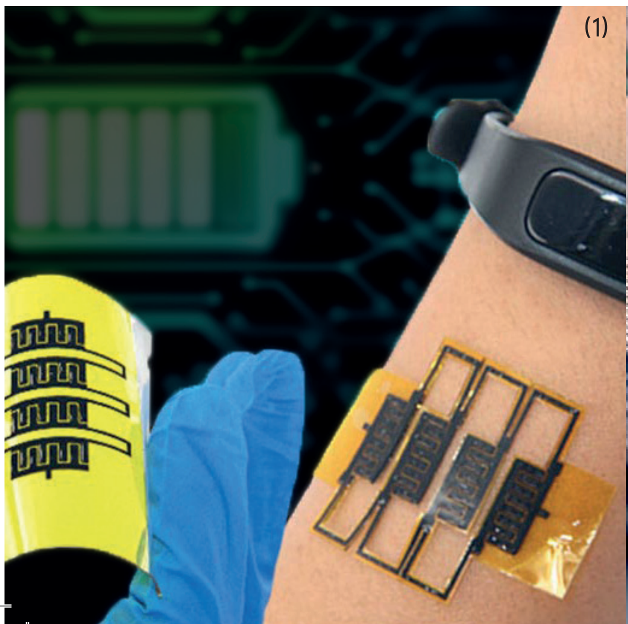


Nanomaterials and nanocomposites are in the spotlight of the search for novel concepts for integration in wearables.

In addition, the conversion of current devices and attachment-based wearables into **integrated technology** may involve a significant **size reduction** while retaining their functional capabilities.

Nanomaterial-based wearable sensors have already marked their presence with a significant distinction while nanomaterial-based wearable actuators are still in their embryonic stage.

(Cover) Fashnerd, mockup of possible application of sensors and LED infused textile; (1) Penn State's Department of Engineering Science and Mechanics, wearable devices that can harvest energy from human breathing and motion; (2) Tactile-sensitive conductive textile sample.



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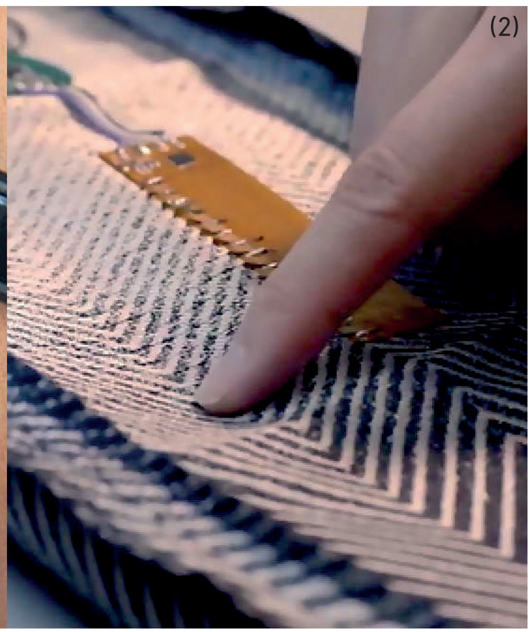

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2.1. Smart textile and nanotechnology

Smart textiles are fabrics that have been designed and manufactured to include technologies that provide the wearer with **increased functionality**.

These textiles have numerous potential applications, such as the ability to communicate with other devices, conduct energy, transform into other materials and protect the wearer from environmental hazards.

- ⊕ Wide range of applications
- ⊕ Improved physical and mechanical performance
- ⊖ Need for conventional metal components
- ⊖ Lack of comfort if not very flexible
- ⊖ Low sustainability

Lumalive

By Philips

Light-emitting textile: beneath the outer fabric a layered system contains flexible arrays of colored LEDs, visible from the outside only when switched on.

https://thefutureofthings.com/5651-philips-lights-your-clothes/

Sensoria

By Sensoria Fitness

A pair of smart socks, comprised of microelectronics, software, and a **sensors-infused textile** that allows you to measure how far and how fast you run with precision.

https://www.sensoriafitness.com/wearables-2-0/

References

Smart Textiles and Nano-Technology: A General Overview. Syduzzaman et al. Journal of Textile Science & Engineering, 2015.

Fibres to Smart Textiles, Advances in Manufacturing, Technologies and Applications. Patnaik, Patnaik. CRC Press 2019.

Nanomaterials for sensor applications. Santiago et al. 2009.

OPPORTUNITY

3.3. Printing responsive cellulose on fabrics

Cellulose-based **3D printing materials** can be used in fabric modifications to install functionalities on fabric surfaces as **light** or **thermo-responsiveness**.

- ⊕ High compatibility between cellulose fabric and print
- ⊕ Renewable and organic
- ⊕ Provides structure and function
- ⊖ Limited mechanical properties
- ⊖ Low weathering resistance
- ⊖ Reduced mechanical properties
- ⊖ Additives reduce biodegradability

Thermochromic cellulose 3D-printed textiles

By P. Varis, Aalto University

Tags 3D-printed onto the fabric with cellulose filament **enriched with thermochromic powder**. If current passes through the conductive thread, heat **alters the color** of the tag.

References
Designing Cellulose For The Future. Kataja, Kääriäinen. DWOC 2013-2018, 2018.

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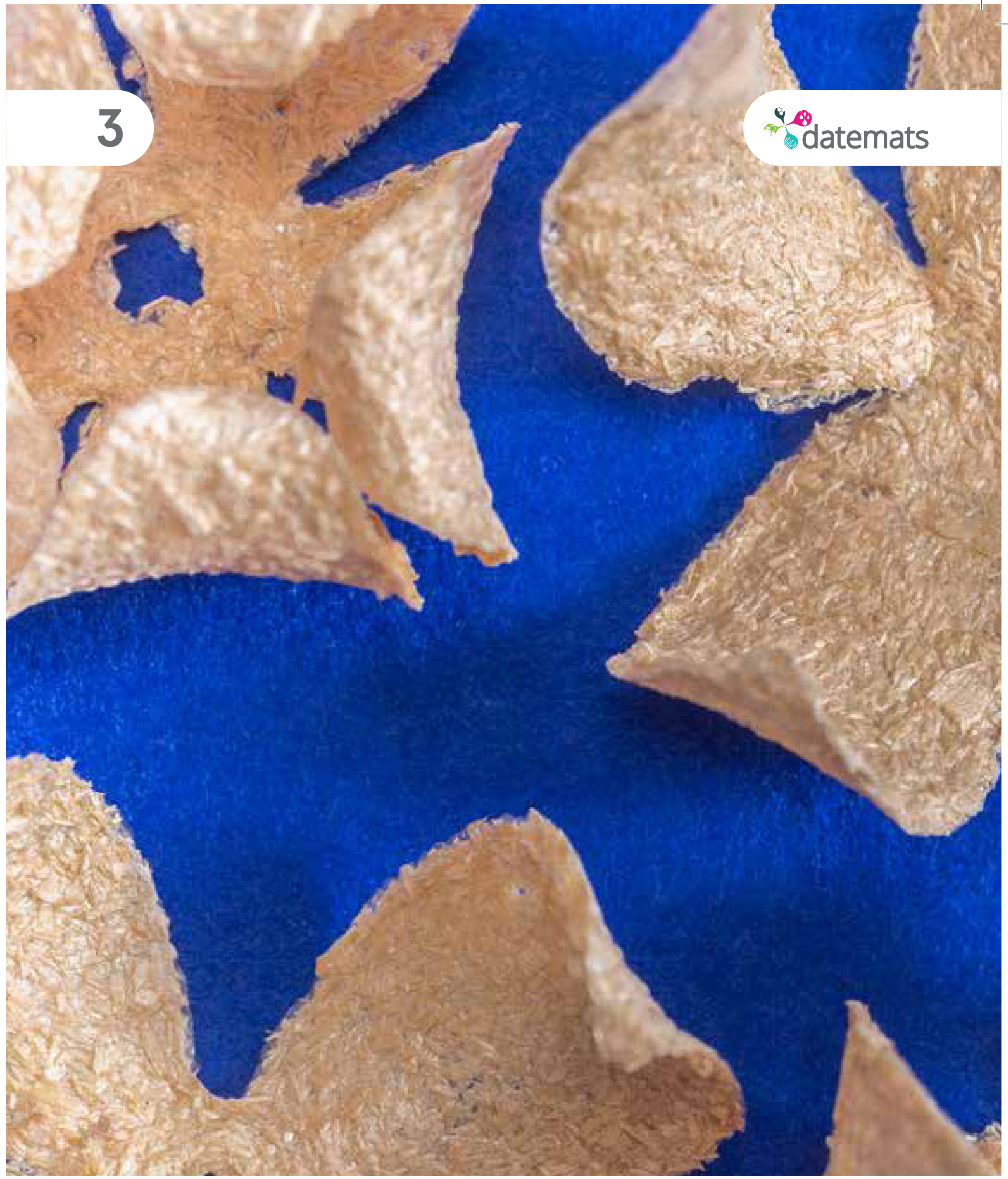
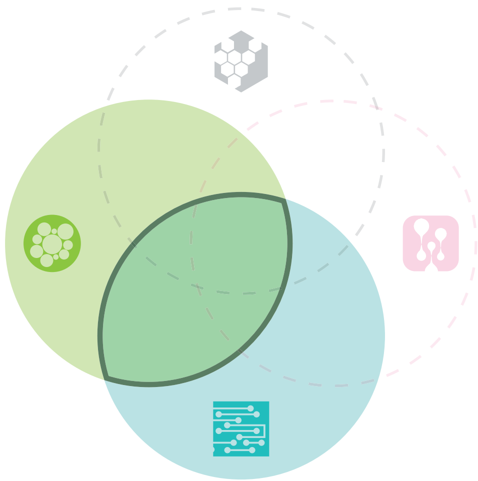


EXPERIMENTAL WOOD-BASED ICS MATERIALS

2-AREAS INTEGRATION

INTEGRATION

3. EXPERIMENTAL WOOD-BASED ICS MATERIALS



One of the main challenges regarding the development and application of ICS materials is delivering final **environment-friendly solutions**, using non-toxic, easy to disassemble, update and repair, durable or recyclable components.

Integrating interactive technologies with renewable and biodegradable **materials and fibers from wood**, such as cellulose, may allow easier separation of parts. Furthermore, cellulose has **unique qualities and properties** that can be used to produce tangible sensing and interactive systems combined with electronics or in substitution of them.

(Cover) Nanocellulose for self-assembly in design by Barron, two-dimensional design, that through the process of drying, would shrink and curl itself; (1) Programmable knitting by Scott, programmed knitwear reacting to moisture; (2) Transformative Paper, by IMD Offenbach, Hundt and BMW, "Intuitive Brain; (3) Thermochromic 3D-printed tags on fabric by Varis, connection of a sample to current.

OPPORTUNITY

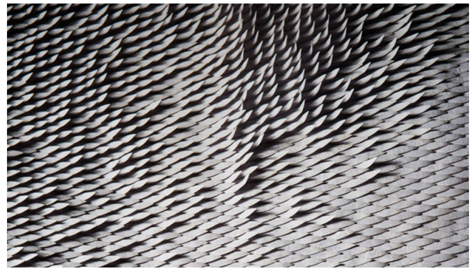
3.1. Cellulose as a responsive material to moisture

Cellulose paper and fibers are **hygroscopic**: when cellulose comes in contact with moisture, water molecules adsorb on their surface. When a particular geometry and configuration is applied, cellulose-based surfaces and textiles **reversibly morph** into various states.

It is possible to determine the geometry related to each deformation and integrate it in the design process by parametric design.

⊕ Alternative sensor/actuator
⊕ Can be both sensor and substrate
⊕ Can be combined with electronics

⊖ Limited mechanical properties
⊖ Low weathering resistance
⊖ Composition limits disassembly



Transformative paper

By F. Hundt, IMD Offenbach

A layered structure, which reacts to short-term **environmental conditions**, morphing into various states.

www.materialdistrict.com/article/transformative-paper-by-florian-hundt/

Programmable knitting

By J. Scott

Shape-shifting textiles, responsive to environmental stimuli and programmed to change in shape **as moisture levels increase**.

https://responsiveknit.com/programmable-knitting/

References

Experimenting and Hybrid Concepts in Material Design. Holzbach. ICS Materials, 2021.

Responsive Knit: The Evolution of a Programmable Material System. Scott. 2018.

OPPORTUNITY

3.2. Cellulose as a self-assembly material

Cellulose performs a shapeshifting behavior when reacting to moisture. On the way around, the shrinking and curling caused by water evaporation from a nanocellulose substance could potentially be applicable in this self-assembly context.

A **two-dimensional design** is created, which, through the drying process, would **shrink and curl** itself into a pre-decided, specific **3D shape**.

⊕ Self-assembling
⊕ Reduced manifacturing process

⊖ Shape design limitation
⊖ Complex design development

Nanocellulose and self-assembly in design

By Barron

Design exploration with nanocellulose, sawdust, plywood and aluminium foil for self-curling decorations.

https://chemarts.aalto.fi/wp-content/uploads/2018/04/CHEMARTS_SummerSchool2017_ESITE_website.pdf

References

The CHEMARTS Cookbook. Kääriäinen et al. Aalto University, 2020.

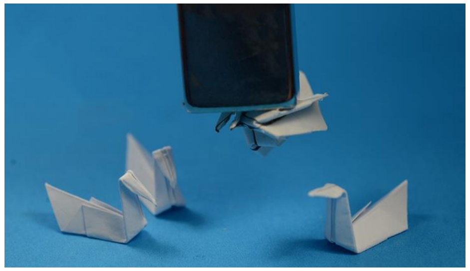
OPPORTUNITY

4.2. Enhanced bacterial cellulose based materials by addition of nanoparticles

Bacterial cellulose-based materials (BC) have unique and interesting **structural, physical, and chemical properties** but lack others (magnetic, electrical conduction, antimicrobial, antioxidant, etc.), which can be added **incorporating** different kind of **nanoparticles**.

The resulting nanocomposites could be potentially applied in several fields: medicine, environmental, info-storage, or electromagnetic shielding.

- ⊕ Advanced properties infusion
- ⊕ High development potential
- ⊖ Possible toxicity
- ⊖ Low biocompatibility



White magnetic paper

By University of Bristol

Flexible, rollable, foldable like normal paper, based on a nanoparticles-infused magnetic BC network sandwiched between two white BC layers.

https://core.ac.uk/download/pdf/161815456.pdf

Graphene + carbonized BC aerogel

By Jiaotong University

Robust, ultralight, recyclable **water purification devices** using BC-graphene nanocomposites, for water-oil separation, organic solvents and metal ions removal.

https://www.sciencedirect.com/science/article/abs/pii/S0008622318306997?via%3Dihub

References

Bacterial Cellulose-based Magnetic Nanocomposites: A Review. Sriplai, Pinitsoontorn. Carbohydrate Polymers, 2020.

Recent development in bacterial cellulose production and synthesis of cellulose based conductive polymer nanocomposites. Poddar, Dikshit. Nano Select, 2021.

Bacterial Cellulose—Graphene Based Nanocomposites. Troncoso, Torres. Int. J. Mol. Sci, 2020.

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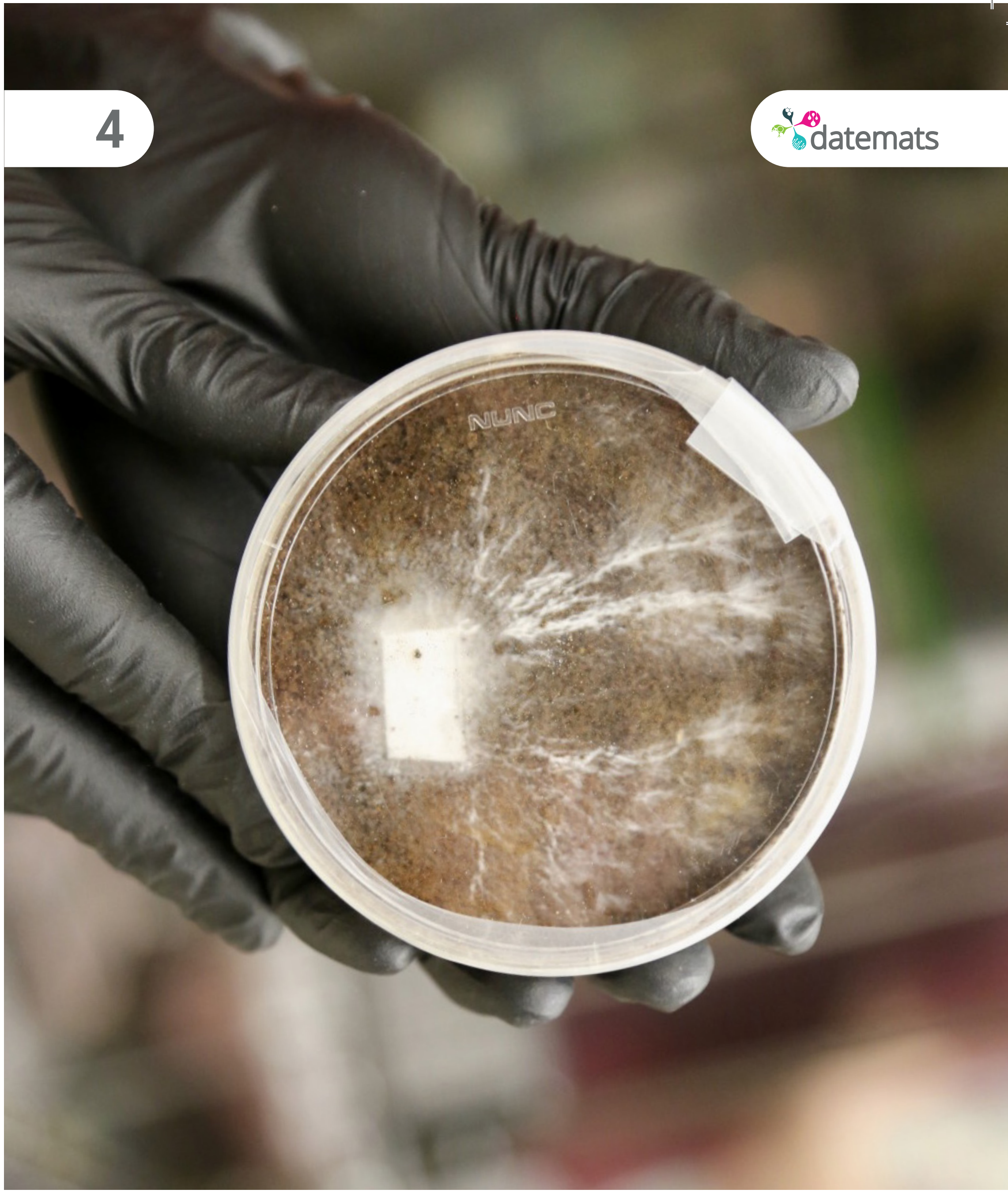
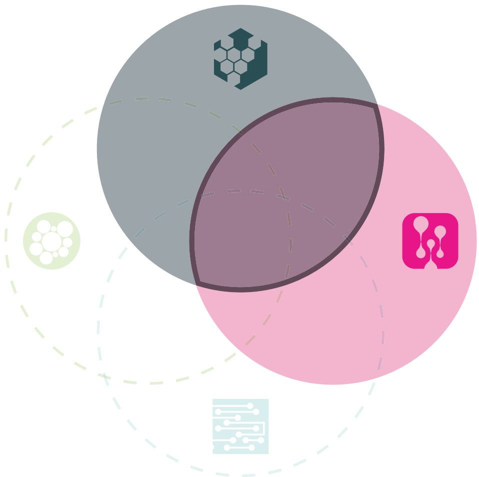


ADVANCED GROWING NANOMATERIALS

2-AREAS INTEGRATION

INTEGRATION

4. ADVANCED GROWING NANOMATERIALS



Bio-fabrication is a new design paradigm centered on advanced growing materials coming from organisms like bacteria or fungi.

A broad spectrum of potential applications suggests that bio-fabrication could become a relevant technological paradigm for 21st century.

Researchers and visionaries from various disciplines, such as architecture, computer science or chemistry, propose the idea of **adding nanoparticles** to infuse key characteristics to these materials (e.g., mechanical resistance, self-healing, magnetic, electrical, or conductive properties).

(Cover) NASA, Mycelia growing on Martian regolith simulant; (1) Georgia Tech University, Arc of tactical mycelium, intermediate trial for the realization of the Monolito Micelio; (2) Bacterial Cellulose: New bio-composites based on bacterial cellulose for architectural membranes, by Damsin.

(1)

(2)

OPPORTUNITY

4.1. Functionalising mycelium to control its growth in monolithic architecture

Due to the low stress capacity of mycelium-based materials, the structural stability of monolithic constructions based on these materials should be achieved through geometry.

Research about computing devices based on fungi supports the idea that **nanotech** could be added to the substrate of mycelium to **"program" its growth**. Fungal buildings would self-grow, build, and repair themselves subject to functional additive.

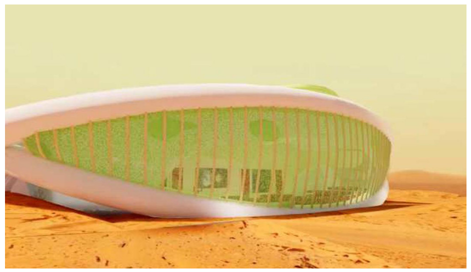
- ⊕ Improved growth control
- ⊕ Living material gains self-healing/self-repairability
- ⊕ Requires water and provide the right condition to enable growth
- ⊖ Nanomaterials be toxic for fungal mycelium

Monolito Micelio bio-pavilion

By Georgia Tech

A **self-supporting** performance structure for a barbershop quartet, made of "programmed" tactical mycelium.

https://jdovaults.com/El-Monolito-Micelio



MushROOMS

By NASA

Exploring technologies to grow fungal structures to become our **future homes on other planets**, and maybe lead to more sustainable ways of living on Earth.

https://www.nasa.gov/feature/ames/myco-architecture

References

Towards fungal computer. Adamatzky. Interface focus, 2018.

Fungal architecture. Adamatzky et al. arXiv, 2018.

Growing Fungi Structures in Space. Woesten et al. ESA, 2018.

OPPORTUNITY

5.2. Wood, mycelium and cellulose microfibrills composites

Replacing formaldehyde-based resins employed in lignocellulosic based composites with CNF to create **100% natural-based composites** in both standard and lightweight categories.

- From 100% natural materials
- Enhanced mechanical properties
- Enhanced phyisical properties

MycoFlex

By Ecovative Design

100% pure mycelium structure, **high-performance foams** to create a variety of material types across a wide range of applications.

https://ecovativedesign.com

Mycelium composite flooring

By Mogu

Resilient circular tiles. Mycelium composite core from agro-industrial residues, coated with a formulation of **90% bio-based resins**.

https://mogu.bio/

References

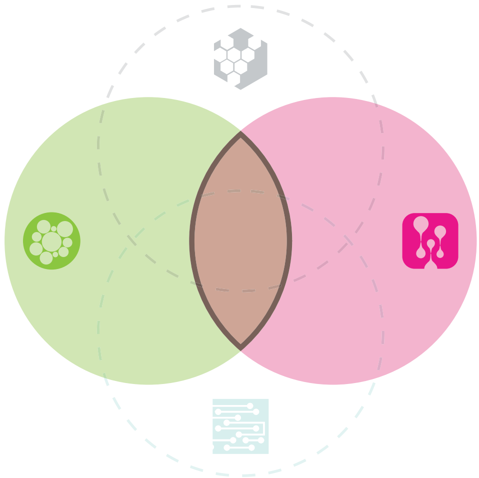
Fully Bio-Based Hybrid Composites Made of Wood, Fungal Mycelium and Cellulose Nanofibrils. Sun et al. Sci Rep 9, 2019.

Engineered mycelium composite construction materials from fungal biorefineries: A critical review. Jones et al. 2019.

ADVANCED GROWING EXPERIMENTAL WOOD-BASED MATERIALS

2-AREAS INTEGRATION

5. ADVANCED GROWING EXPERIMENTAL WOOD-BASED MATERIALS



Growing materials afford the possibilities of using 'waste' as a feeding substrate to implement **truly circular** material approaches.

Waste from the wood industry such as chips, shavings and sawdust can be used in the making of mycelium products, taking advantage of both components, exploiting **mycelium binding characteristics** to grow the resulting material into the final shape manifestation.

(Cover) Blast Studio, 3D-printed furniture of mycelium composite; (1) Caracara Collective and BIOHM, mycelium tiles grown into shape; (2) Blast Studio, mycelium 3D-printing process.

5.1. Mycelium-based panels grown to form

Replacing synthetic plastic polymers with natural mushroom based polymers to bind wood 'waste' into boards and shaped products. They can be applied to furniture, packaging, acoustic panels and other applications, for their antishock and insulation properties and their lightweight quality.

Besides growing in a mold to give shape to a product, some designers experimented with **3D printing**.

- (+) From 100% natural materials
- (+) Can grow into shape
- (−) Low water resistance
- (−) Low weathering resistance

3D printed mycelium

By Blast Studio

Using biomaterial from waste and mycelium to 3D print unique artefacts with **shapes inspired by nature**.

https://www.blast-studio.com/

Mycelium acoustic panels

By Mogu

Exploiting natural **sound absorbing qualities** of the composite, modular panels are grown into form, giving different shapes and aesthetic textures.

https://mogu.bio/

References

When the material When the Material Grows: A Case Study on Designing (with) Mycelium-based Material. Karana et al. International Journal of Design, 2018.

Development of an extrudable paste to build mycelium-bound composites. Soh et al. Material & Design, 2020.

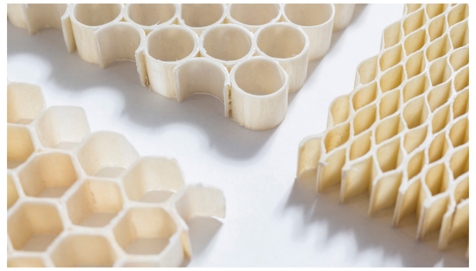
OPPORTUNITY

6.3. Bio-based solid materials or composites

Nanofibrillar cellulose (NFC) or microfibrillar cellulose (MFC) can be used in composites or even as a solid material, potentially to **replace some plastics**.

As these materials typically react to water, the water resistancy needs to be enhanced for example by adding a separate layer.

- ⊕ From renewable materials
- ⊕ Non-toxic
- ⊕ Pleasant feeling to touch
- ⊕ Low water resistance, without coating
- ⊖ Complex manifacturing, due to high shrinkage
- ⊖ Not thermoformable

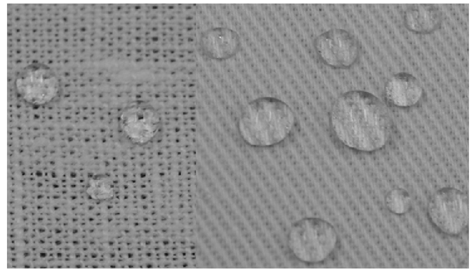


Uses and processing of MFC

By DWoC, various

It can be processed using moulding technology into extremely **light, strong 3D forms**, structures and constructions that are based on the chemical bonding of cellulosic fibres.

https://cellulosefromfinland.fi/



Hydrophobic coating for MFC

By Forsman

Bio-based, layer-by-layer assembled hydrophobic coatings for cellulose nanofibril films and textiles, made of **polylysine and natural wax particles**.

https://doi.org/10.1016/j.carbpol.2017.06.007

References

Plastic-like packaging material made from completely renewable raw materials by VTT

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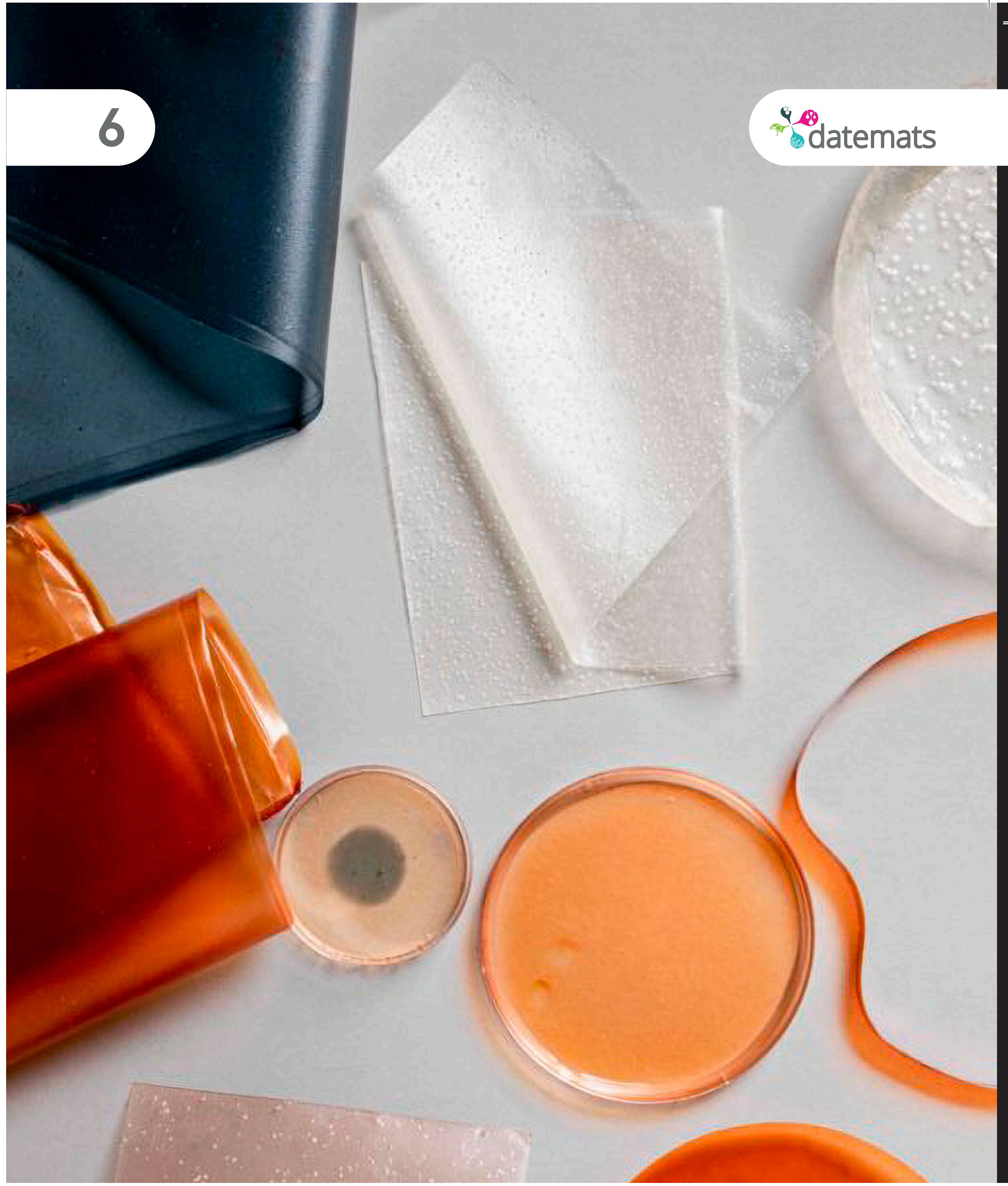
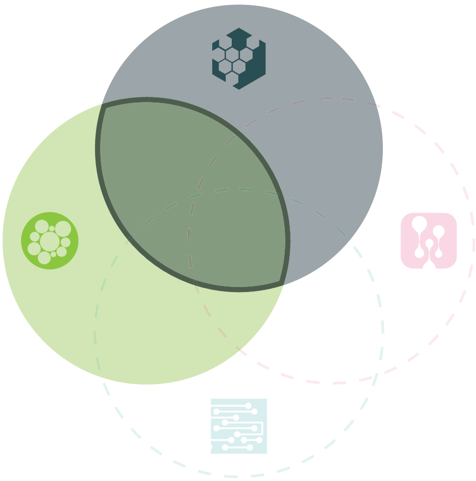


EXPERIMENTAL WOOD-BASED NANOMATERIALS

2-AREAS INTERATION

INTEGRATION

6. EXPERIMENTAL WOOD-BASED NANOMATERIALS

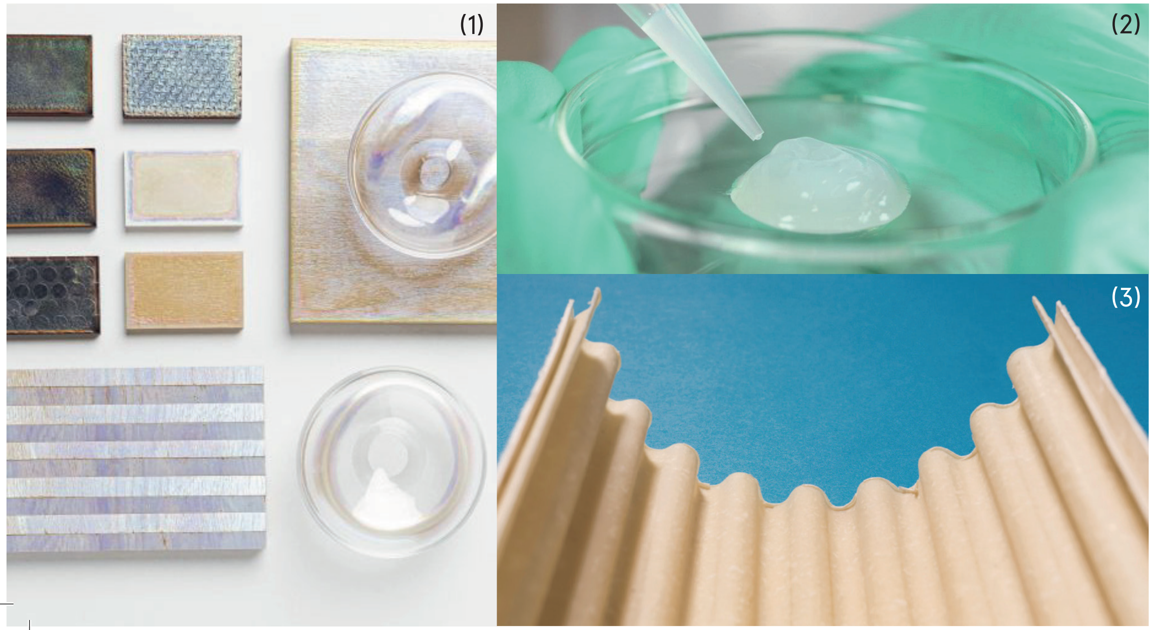


Wood-based materials can be **nano-scaled** (e.g., nanocellulose) or be **coated with nanomaterials**.

Nanocellulose is not a singular material: several wood-based materials have micro- or nano-structured fibrils. They can be used as fillers, binders and coatings or for composites.

They are mainly biodegradable and **biocompatible**, and have been researched – for example – as an **option to replace plastics**. However, as the water resistance of these cellulose-based materials is usually not very good, the first real-life applications are tested in areas in which water resistance is not essential.

(Cover) CHEMARTS, Aalto University, by Suorlahti, transparent sheets made of nanofibrillar cellulose (NFC); (1) Structural colour from nanocellulose by Noora Yau & Konrad Klockars at Aalto University, photo Eeva Suorlahti; (2) GrowDex, nanofibrillar hydrogel by UPM Photo: UPM; (3) Corrugated sheet structures from nanocellulose, by Härkäsalmi.



OPPORTUNITY

6.1. Nanocellulose for medical and life science applications

Nanofibrillar cellulose (NFC) is a (semi) transparent gel of cellulose fibrils in water.

- ⊕ Bio-compatible
- ⊕ Medically safe
- ⊕ Bio-degradable
- ⊕ Properties can be tailored

- ⊖ High-tech, high cost
- ⊖ Low water resistance

FibDex

By UPM biomedicals

Eco-friendly growing medium for cell culture applications and self-detaching **wound dressings**, that keeps the skin moisture in balance.

https://www.upmbiomedicals.com/for-clinical/fibdex/

References

Cellulose Nanomaterials Review: Structure, Properties and Nanocomposites. Moon et al. Chemical Society Reviews, 2011.

Super Materials from Wood: Cellulose, Hemicellulose and Lignin. Kangas. Lost in the Wood(s): The New Biomateriality in Finland, 2017.

OPPORTUNITY

6.2. Nanocellulose for functional coatings

Nanocellulose has proved to be a versatile material for **functional coatings**. Certain type of nanocellulose can be used to create **structural color** surfaces on various materials, or as **fire-retardant** on wood.

- ⊕ Non-toxic
- ⊕ Properties can be tailored

- ⊖ Low water resistance

Shimmering structural coating

By Structural color studio

Non-toxic, resistent to sunlight and environment-safe alternative to additive pigments. The color variation are generated **through a physical treatment creating optical effect.**

https://structuralcolourstudio.com/shimmering-wood/

Cellulose nanofibril coating as paint

By Pere, Kunnari, Turunen

Eco-friendly surface treatment based of nanofibril coating. **Non-permanent, water-removable**, usable for temporary protection during transport, or as dressing paint.

https://cellulosefromfinland.fi/

References

Asymmetrical coffee rings from cellulose nanocrystals and prospects in art and design. Klockarset al. Cellulose, 2019.

Visual Potentials of Translucent Cellulose Nanofibril Films Produced from Renewable Resources. Turunen, Kunnari. International Conference on Advances on Sustainable Cities and Buildings Development, 2017.

Dyed Cellulose Nanofibril Coating as Paint. Kunnari et al. Forest Products Society's 71st International Convention, 2017.

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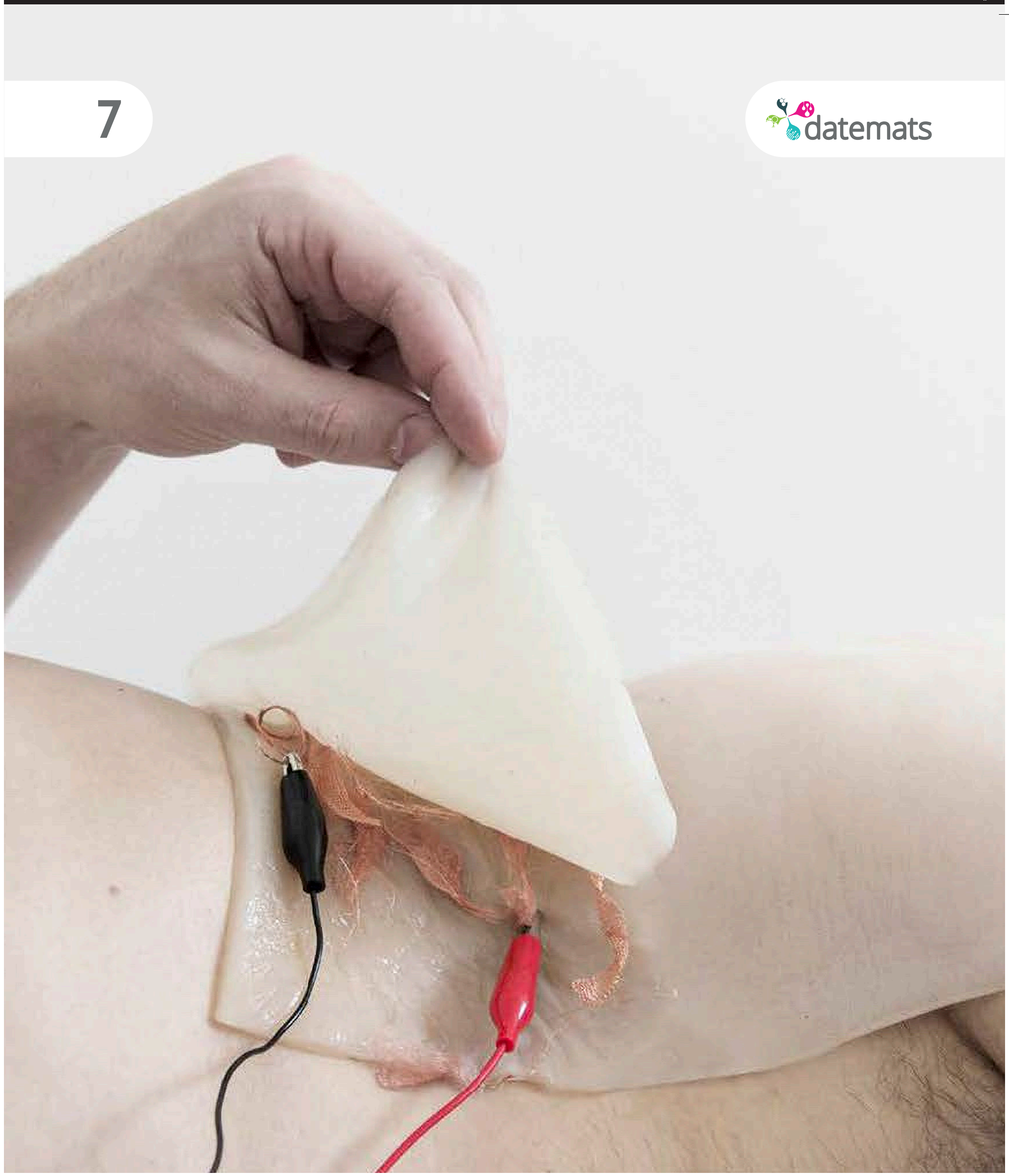
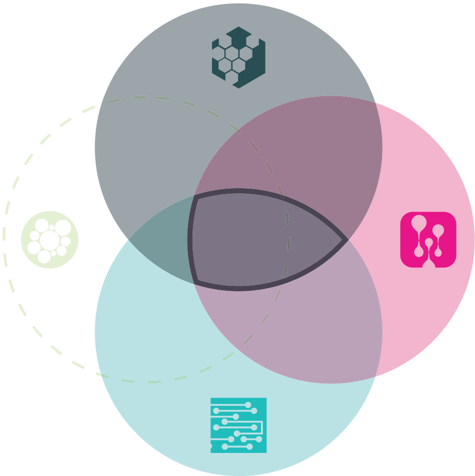


ADVANCED GROWING NANO-ICS MATERIALS

3-AREAS
INTEGRATION

INTEGRATION

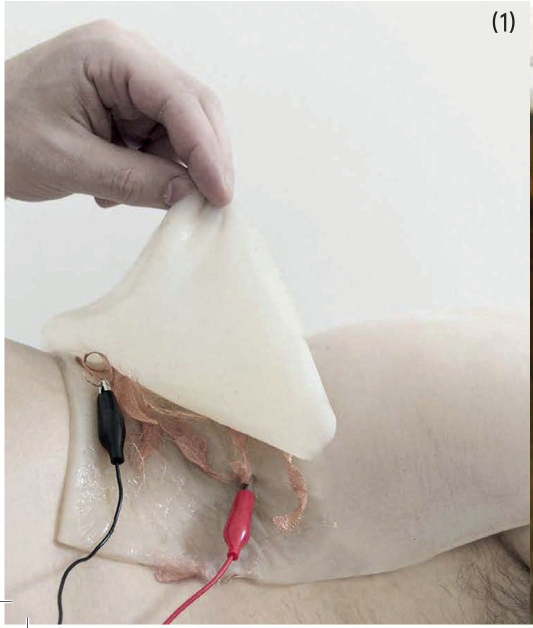
7. ADVANCED GROWING NANO-ICS MATERIALS



Adjacent to and expanding the growing field of organic electronics that are used for **transmission of light**, **photovoltaic** applications or as transistors.

Combining grown materials (such as bacterial cellulose or mycelium) with nanomaterials can create **conductive material behaviors** that can expand above applications to sensing second-skin interfaces for implementation in a number of ICS applications.

(Cover) (1) G. Tomasello, conductive bio skin; (2) G. Tomasello, Growing kombucha with conductive compounds: graphite powder, metal filament, conductive ink.



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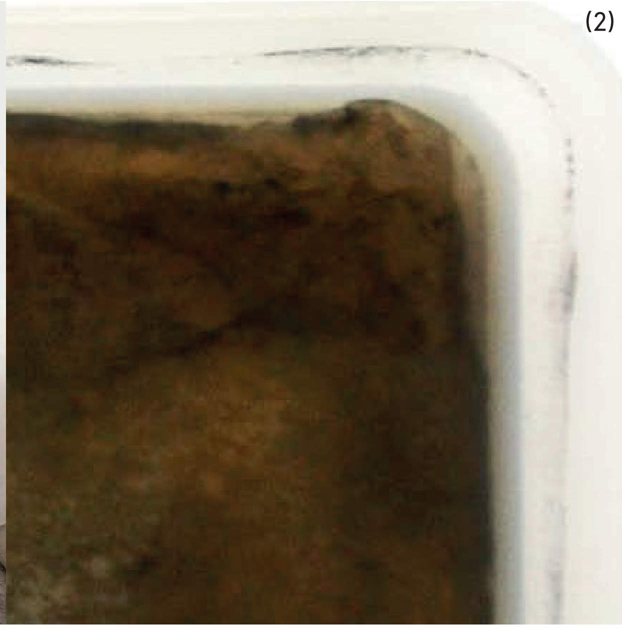

(2)

OPPORTUNITY

7.1. Bacterial cellulose with conductive properties

Growing a bio-conductive material as second skin (here even envisioned to be feeding of the skin’s nutrients) that can operate and move in symbiosis with the first skin and enable advanced sensing of the environment.

Also, bacterial cellulose helps the fabrication of wave-shaped lamellae by acting as a highly flexible nano-binder for MXene nanosheets for applications in wearable electronics and electronic skins.

- (+) Bio-integration into the skin’s ecosystem
- (+) Advanced sensing
- (+) Flexibility/stretchability
- (+) Adaptability to the body
- (−) Limited mechanical properties
- (−) Early development stage
- (−) Still conceptual application

SCOBY-based Conductive Bio Skin

By G. Tomasello

Project exploring the potential for augmenting living tissue with electronic components and conductive materials, mimicking the relationship with the skin micro-flora.

https://gitomasello.com

References

Bio Conductive Skin. Tomasello. 2016.

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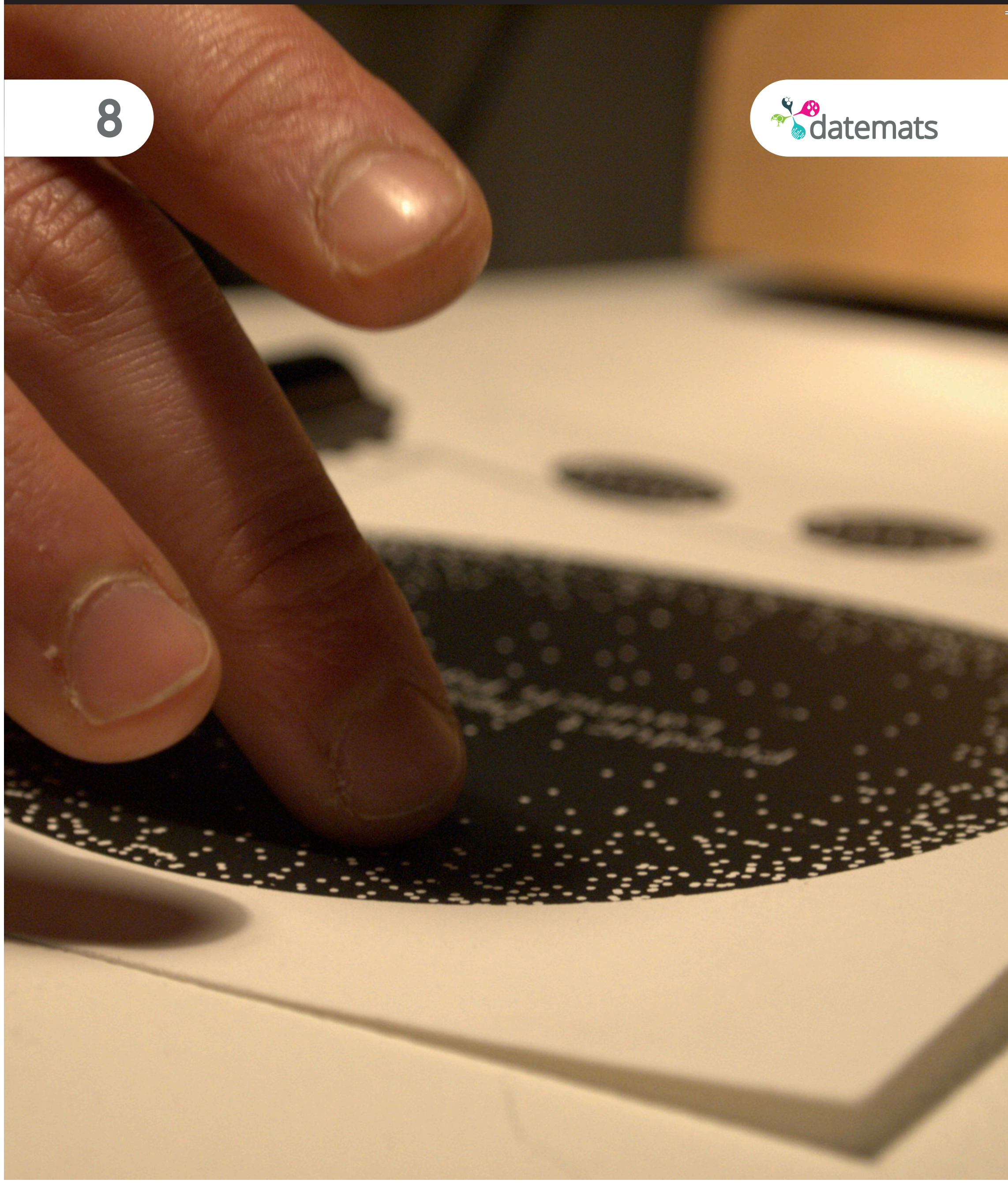
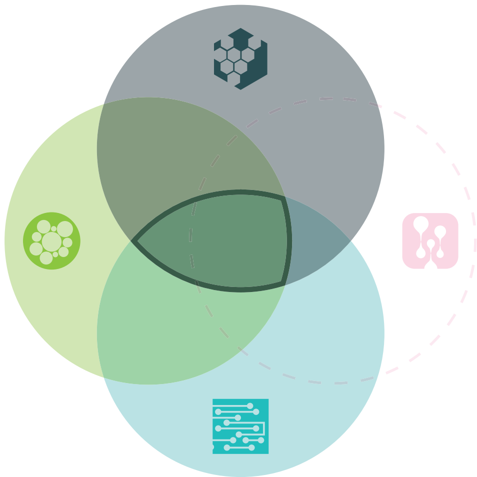


EXPERIMENTAL WOOD-BASED NANO-ICS MATERIALS

3-AREAS INTEGRATION

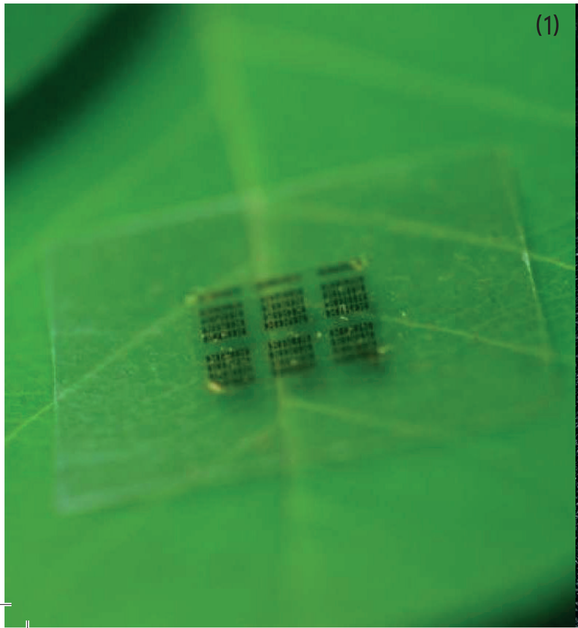
8. EXPERIEMNTAL WOOD-BASED NANO-ICS MATERIALS

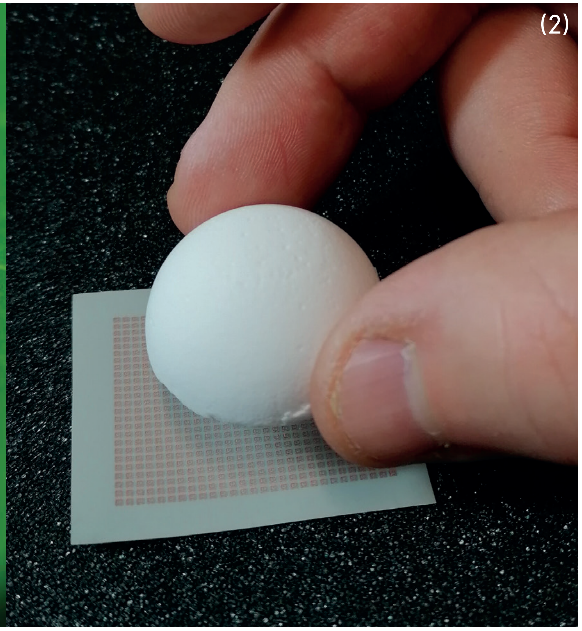


ICS materials and nanomaterials applications **might lack environment-conciusness**. Using non-toxic, easy to disassemble, update and repair, durable or recyclable components could meet this essential goal.

Integrating interactive technologies, conductive materials and smart inks with renewable and biodegradable materials and fibers from wood, such as cellulose, may allow easier separation of parts. This may lead to **transient electronics**, that are **biodegradable** electronic devices and **dissolvable** circuit boards made of organic materials.

(Cover) Musical artworks with paper electronics, Shorter, when scrubbing the surface with the finger, the Bare Conductive paint allow the system to recieve a signal; (1) Example of wood-based microchip to be implanted in paper for biodegradable electronics; (2) University of Oulu, composite lens made of nanocellulose for 6G frequency, about 800 antennas.





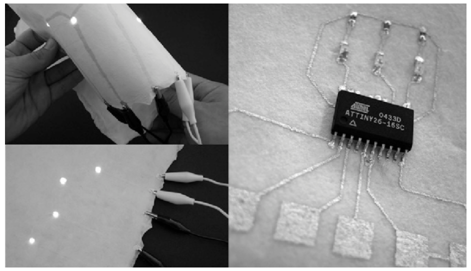
8.1. Paper as a substrate for flexible electronics

Paper can be **substrate** for flexible electronics, combining smart material, papermaking and printing techniques with **conductive** and **smart inks**.

By integrating electrically active inks and fibers in combination with actuators and sensors **directly during the papermaking process**, it is possible to create electronics that behave, look and feel like paper. Conductive materials can be integrated in the paper itself making it conductive.

- ⊕ Detachable/reusable electronics
- ⊕ Low-tech/cost effective process
- ⊕ Allows tinkering and repair
- ⊕ Tech integrable in manifacturing
- ⊕ Partially easily biodegradable

- ⊖ Limited mechanical properties
- ⊖ Low weathering resistance
- ⊖ Limited applications

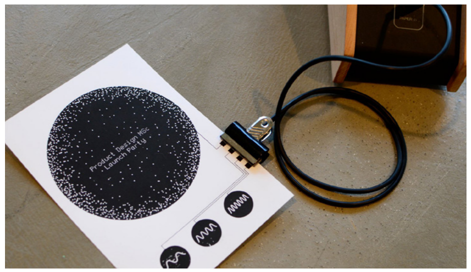


Pulp-based computing

By Ambient Intelligence, Concordia University

Explorations in sensors and actuators that behave, look, and feel like paper.

https://www.media.mit.edu



Musical artworks with paper electronics

By M. Shorter

Interactive paper flyer connected to a speaker, allowing to control the pitch and the frequency of the audio **through the touch**.

https://www.instructables.com/Paper-Electronics-Make-Interactive-Musical-Artwo/

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Pulp-based computing: A framework for building computers out of paper. Coelho, Hall, Berzowska, Maes (2009). CHI EA '09.

Paper as a Substrate and an Active Material in Paper Electronics. Khan, Nassar, Hussain (2021). ACS.

Wood-Based Flexible Electronics. Fu, Chen, Sorieul (2020). ACS Nano, 14, 3.

Transparent and conductive paper from nanocellulose fibers. Hu et al. (2013). Energy and Environment Science.

OPPORTUNITY

9.2. Interactive and living materials

As the world becomes more aware of the implications of the rising global temperature, there is a need for alternative solutions and inspiring visions for the future.

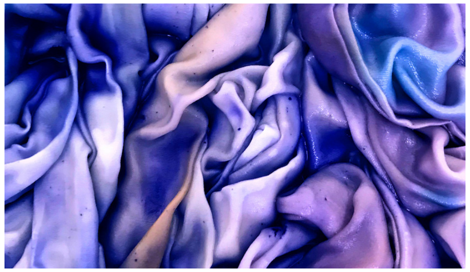
- ⊕ From natural materials
- ⊕ Use biological processes (e.g., photosyntesis)
- ⊖ Sensitive to environment
- ⊖ Need constant care

Carbon Capturing Images

By A. Asif, V. Guccini

It explores the potential of prokaryotic microorganisms (synechocystis), that can **perform photosynthesis to create living images** and biomaterials.

https://chemarts.aalto.fi/wp-content/uploads/2021/04/Aalto-CHEMARTS-summer-school-2020.pdf



The Slow Fashion Start-Up

By Post Carbon Lab

Using Photosynthesis to Create Climate Positive Clothing: **photosynthesising fabric coatings**; **zero-waste bacterial dyes**.

https://eco-age.com/resources/slow-fashion-start-using-photosynthesis-create-climate-positive-clothing/

References

What is photosynthesis? https://www.britannica.com/science/photosynthesis

Carbon positive: Turning a planetary pollutant into an asset. https://www.nesta.org.uk/feature/tipping-point/carbon-positive-turning-planetary-pollutant-asset/

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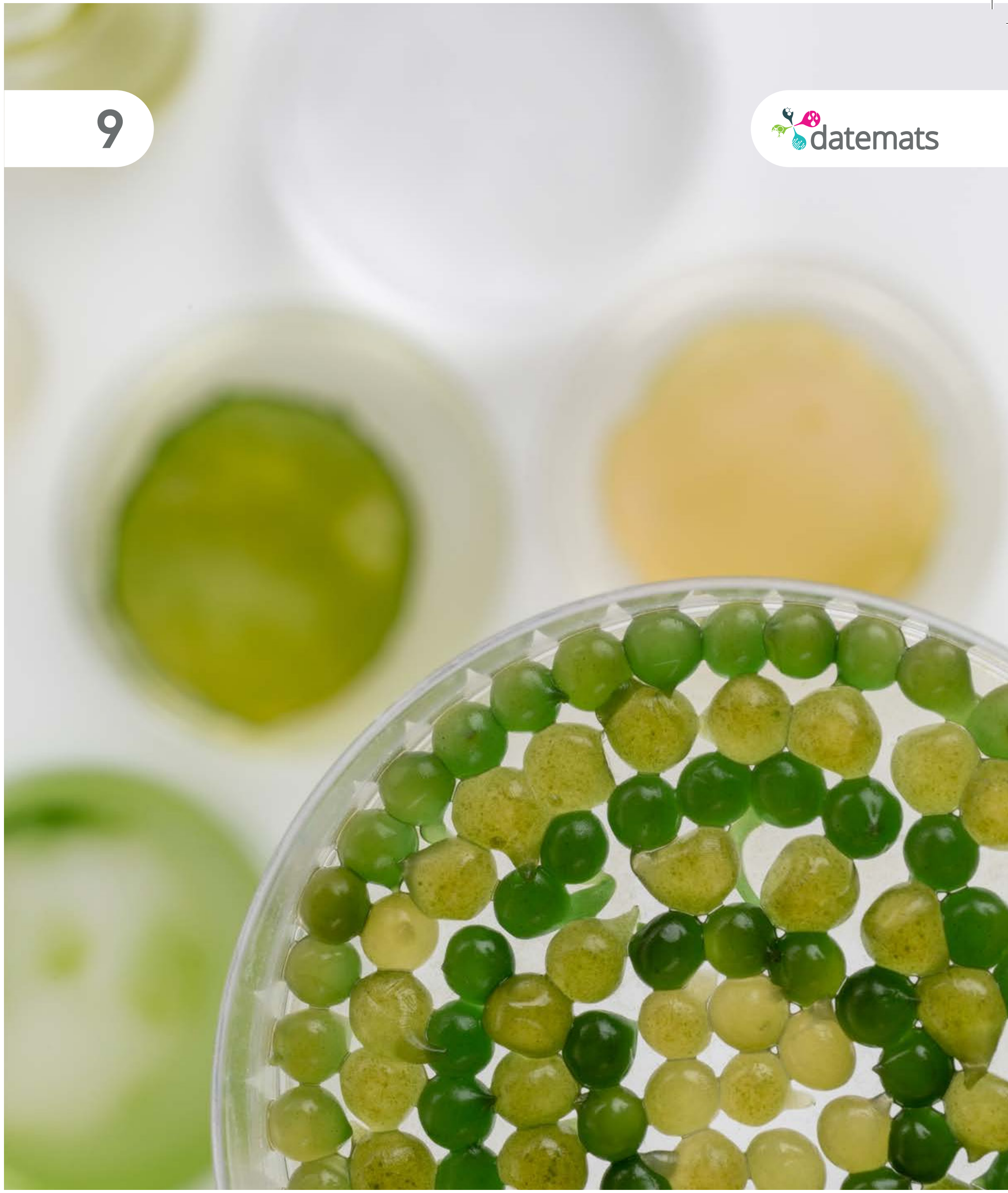
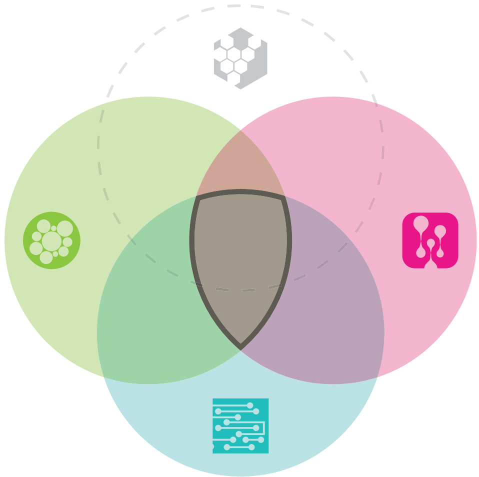


EXPERIMENTAL WOOD-BASED ADVANCED GROWING ICS MATERIALS

3-AREAS INTEGRATION

INTEGRATION

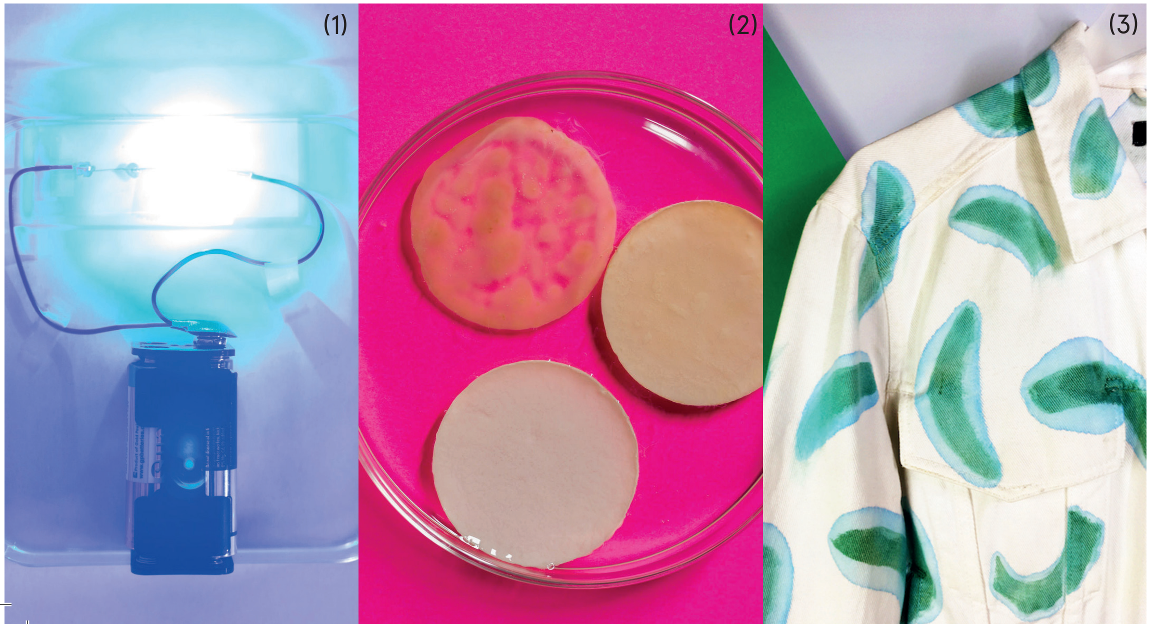
9. EXPERIMENTAL WOOD-BASED ADVANCED GROWING ICS MATERIALS



The combination of these three emerging materials or technologies is quite futuristic. However, this kind of innovative and bold approach is needed to transfer our material environment towards **sustainability** and **circularity**.

Wood-based materials can be used as a matrix to grow either mycelium or bacterial cellulose, to create **interactive and functional materials**, layer by layer structures or composites.

(Cover) Carbon Capturing Images, by Asif, Guccini; (1) Cellulose-based materials can be conductive. Ling Wqang & al. DWoC project 2018, Photo: Eeva Suorlahti; (2) Experiments with kombucha by Inka Mattila CHEMARTS 2018, Aalto University Photo: Eeva Suorlahti; (3) Example of apparel decorated by photosyntesis, by Post Carbon Lab.

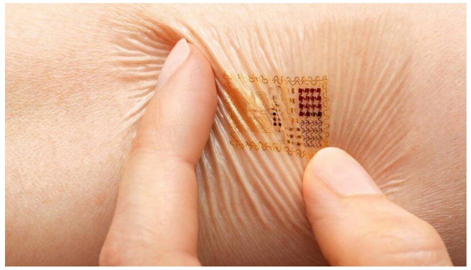


OPPORTUNITY

9.1. Grown or wood-based materials for interactive and smart composites

In the future, synthetic materials such as plastics can be replaced by bio-based or biologically produced materials as matrix materials in wearables.

- ⊕ Hydrophilic, porous, hydrogen bonding
- ⊕ Bio-compatible for human skin
- ⊕ Partially bio-degradable
- ⊕ Partially recyclable
- ⊖ Electronics still traditional
- ⊖ Sensitive to umidity



PCBs on kombutcha nanocellulose

By US Naval Research Laboratory

Skin-thin biometric sensors, printed circuit boards on ultra-thin sheets of nanocellulose, grown in a vat of kombutcha bacteria.

https://techlinkcenter.org/news/navy-using-kombucha-bacteria-to-make-ultra-thin-wearable-sensors

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Myco-accessories: Sustainable wearables with biodegradable materials. Lazaro Vasquez, Vega. ISWC, 2019.

Capacitive storage in mycelium substrate. Beasley et al. UCL, UWE, 2020.

Modifying Native Nanocellulose Aerogels with Carbon Nanotubes for Mechanoresponsive Conductivity and Pressure Sensing. Wang et al. Advanced Materials, 2013.

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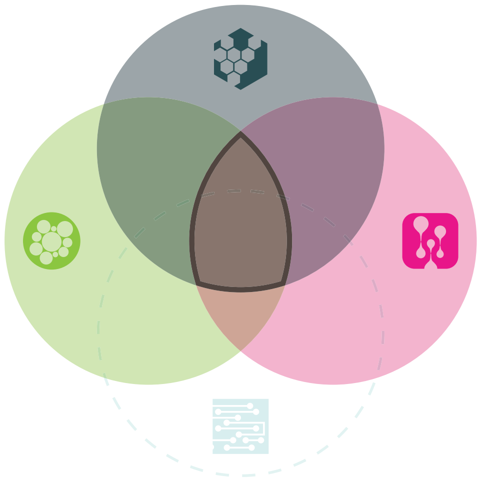
EXPERIMENTAL WOOD-BASED ADVANCED GROWING NANOMATERIALS

3-AREAS INTEGRATION

10. EXPERIMENTAL WOOD-BASED ADVANCED GROWING NANOMATERIALS



Current **lignocellulosic-based composites** are eco-friendly compared with synthetic materials. However, the natural particles are still joined by formaldehyde-based resins whose emissions have been categorized as carcinogenic and toxic to humans. These products include hardwood plywood or medium density fiberboard.

Novel hybrid panel composites **based on wood, fungal mycelium, and cellulose nanofibrils** (CNF) are being developed and investigated to get more **ecofriendly alternatives**.

(Cover) Wood 2.0: cellulose nanofibrils (CNF) for building panels developed by the University of Maine; (1) Growlamps, by Ecovative, lampshades made of mycelium sold in kits for DIY furniture; (2) Mushroom heavy shipping packaging; (3) Wood 2.0, close-up of a pane

(1)

(2)

(3)

10.1. Packaging and furniture applications

These new materials, that incorporate wood particles treated with fungus where additional bonding is provided by cellulose nanofibrils CNF, are suitable for products with **exceptional physical and mechanical properties** for furniture, packaging, handling and transportation, unattainable through conventional chemistry.

- ⊕ Dimensional stability
- ⊕ Water-resistance if using resins
- ⊕ Good thermal/acoustic insulation
- ⊕ 100% plant-based
- ⊕ Bio-degradablility
- ⊖ Hygroscopic if not treated
- ⊖ Uncomplete material properties documentation

Mycelium lights

By N. Meiri

Series of table lamps using mushroom mycelium, as an **alternative to synthetic materials**.

https://www.nirmeiri.com/mycelium-lights

Mushroom packaging

By Dell Technologies

Cushions for **heavy shipments**, grown from agricultural waste and mushrooms and then dried in kiln.

https://www.dell.com/learn/bo/en/bocorp1/corp-comm/mushroom-packaging

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Fully Bio-Based Hybrid Composites Made of Wood, Fungal Mycelium and Cellulose Nanofibrils. Sun et al. Sci Rep, 2019.

Laminated Wallboard Panels Made with Cellulose Nanofibrils as a Binder: Production and Properties. Hafez, Tajvidi. Materials, 2020.

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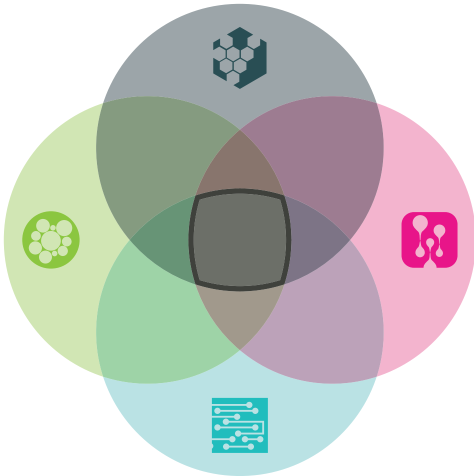
EXPERIMENTAL WOOD-BASED ADVANCED GROWING NANO-ICS MATERIALS

4-AREAS INTEGRATION

INTEGRATION

11. EXPERIMENTAL WOOD-BASED ADVANCED GROWING NANO-ICS MATERIALS



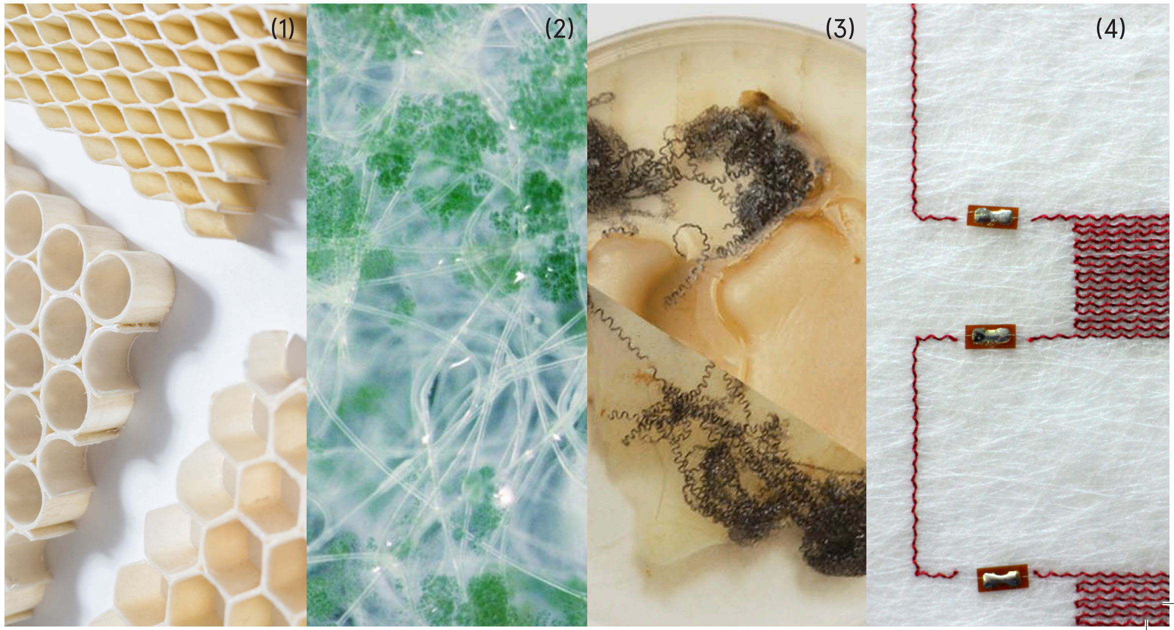
This integration is the most complex, and at the same time the most promising and rich of potential.

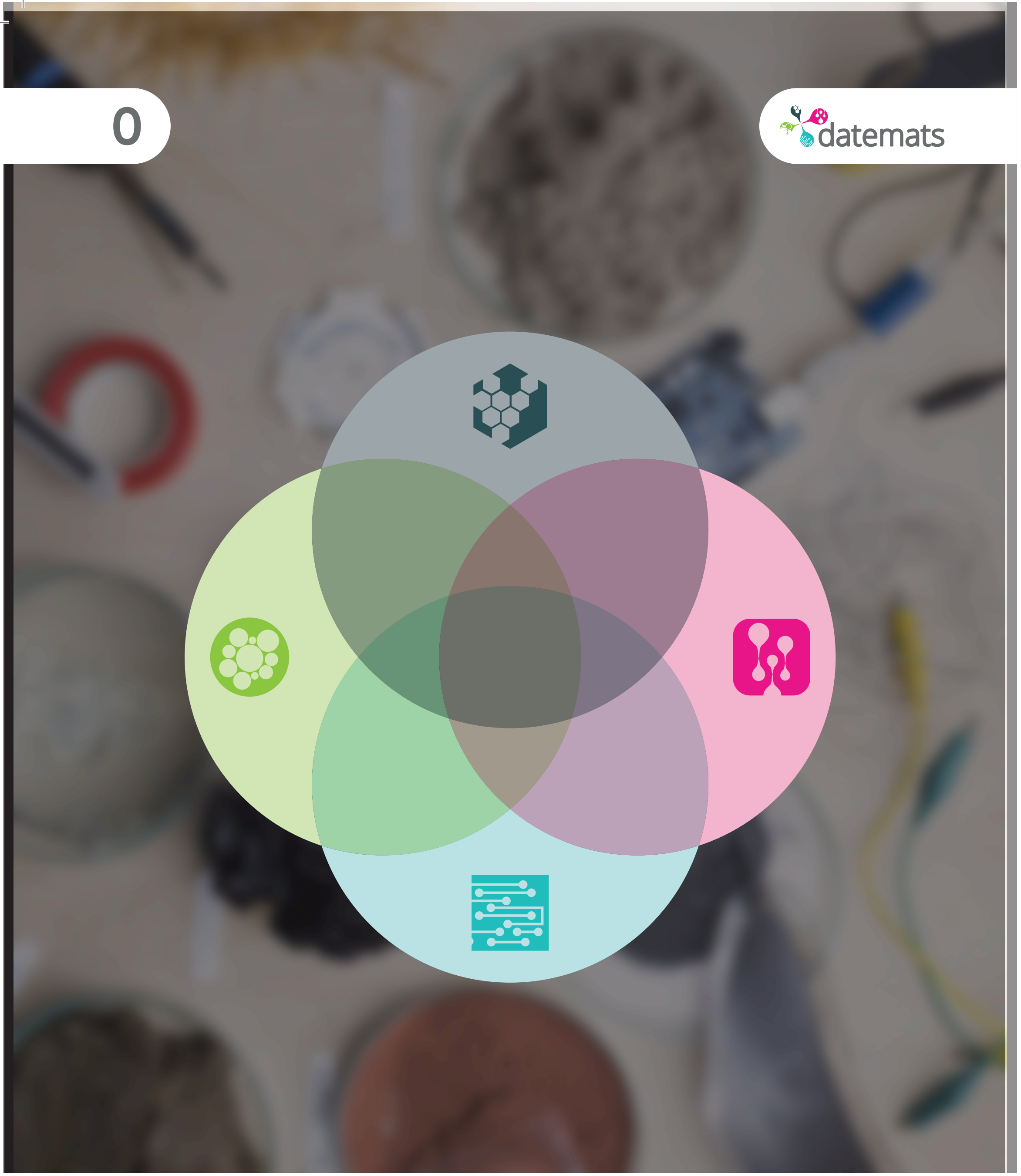
It's up to you.

There are virtually endless possibilities to combine all four areas together, mixing and matching qualities, properties and potential of emerging materials.

This is your challenge as researchers, designers and creatives.

(Cover) Symposium: Material as Experiment; (1) Panels of geometrical structure from nanocellulose, by Härkäsalmi; (2) Close-up of photosyntesis as dying process, by Post Carbon Lab; (3) Conductive kombucha, by G. Tomasello; (4) Conductive thread circuit stitched on textile.





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11. EXPERIMENTAL WOOD-BASED ADVANCED GROWING NANO-ICS MATERIALS

ICS materials

Advanced growing materials

Nano-materials

Experimental wood-based materials