Wood Nanoscience and Nanotechnologies



Liangbing (Bing) Hu

Founding Director, Yale's Center for Materials Innovation

Carol and Douglas Melamed Professor

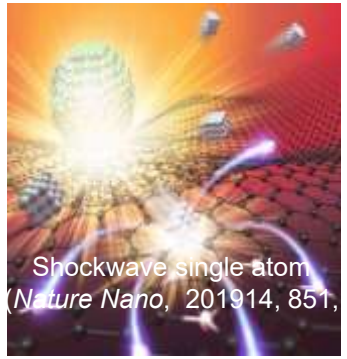
Electrical and Computer Engineering, Materials Science

Yale University

Maine Forest Biomaterials Week

October 8, 2026

HighT-Tech Inc





Electrified Heating
(non-equilibrium synthesis)
- ***High entropy catalysts***
- ***Membranes***
- ***Green fuel***









WH-Power Inc

Energy Storage
(Solid-state)
- ***New electrolytes***
- ***Devices***
- ***Grid, transportation***

Materials Innovations

Sustainability
(Engineered Wood)
- ***Mechanics/Structure***
- ***Energy efficiency (buildings)***
- ***Ion/fluidic (energy/water)***



USPlasma Inc







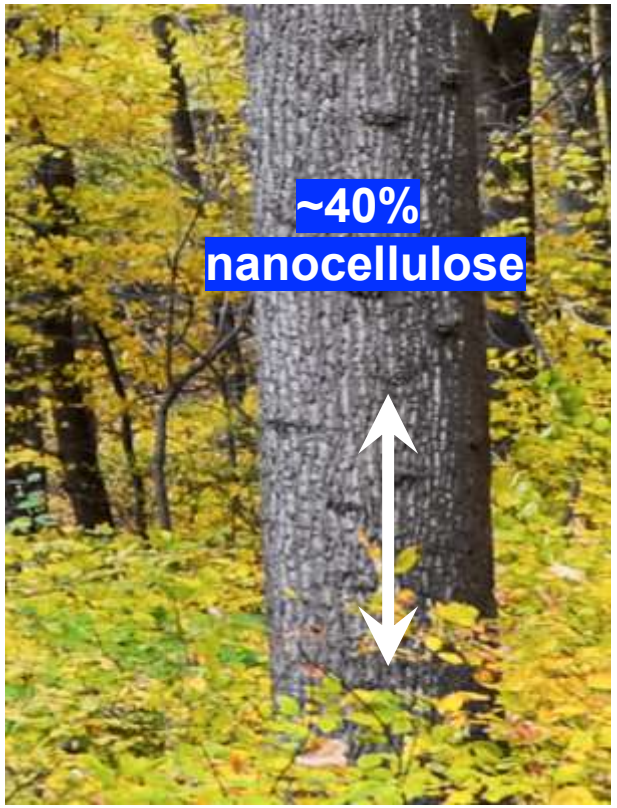


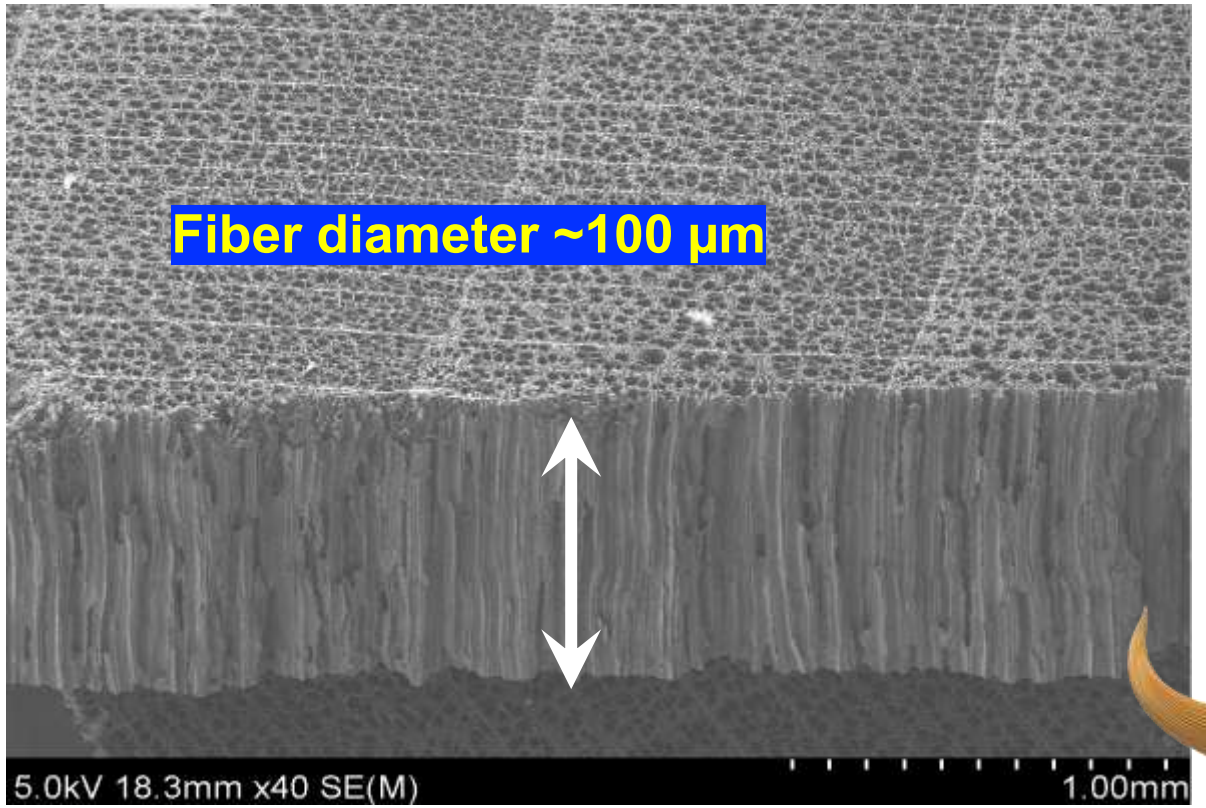


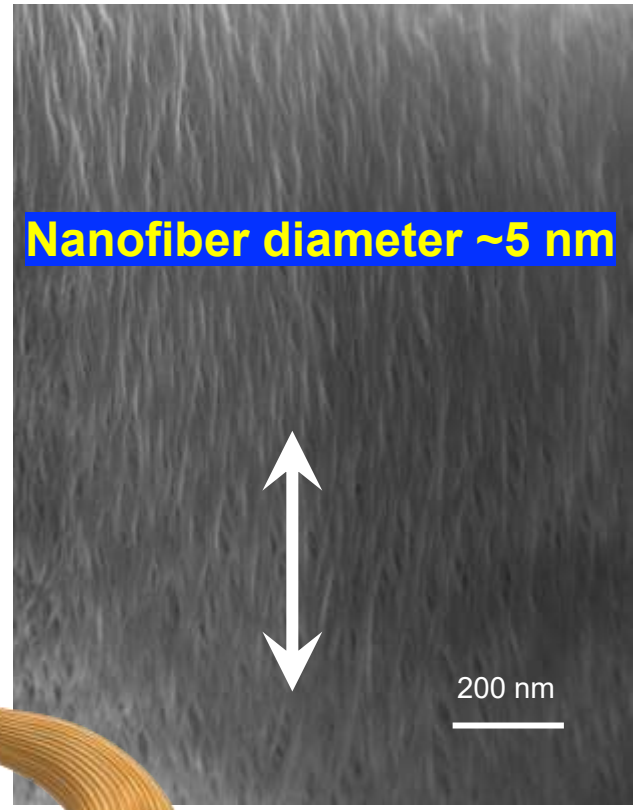
Headquarter and SuperMill 1



Nanofibers from Wood

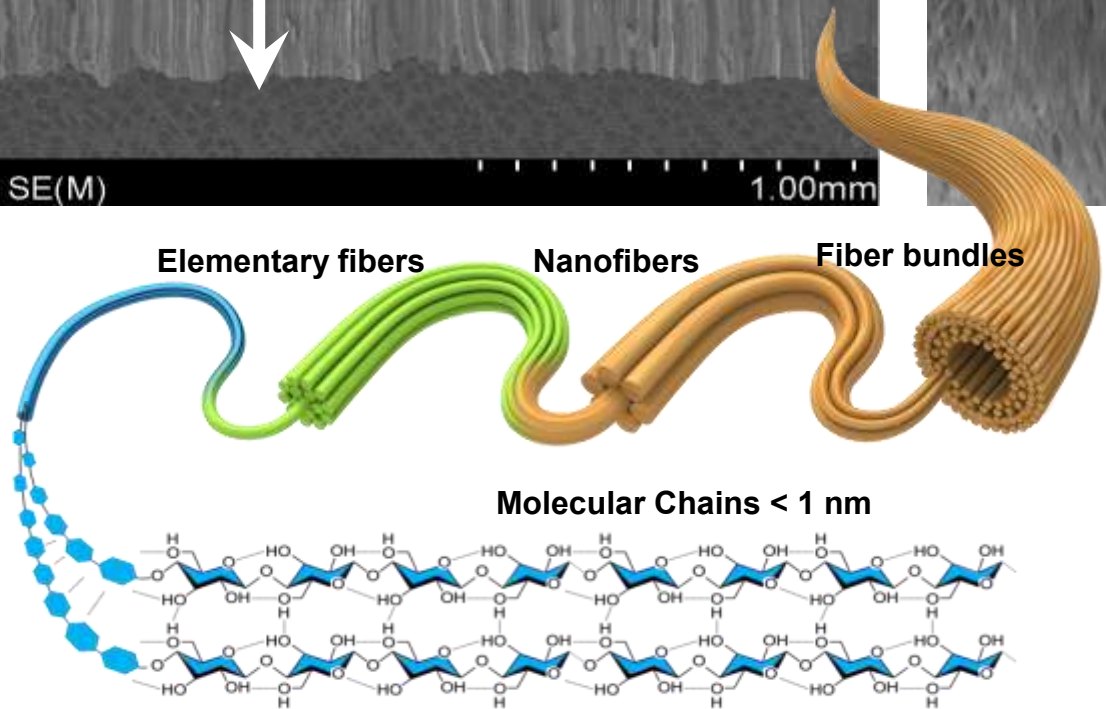






Cellulose Nanofibers

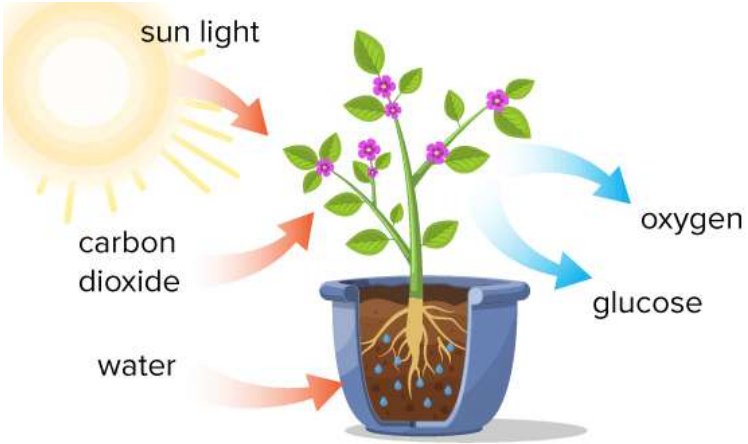
- Diameter ~ 5nm
- ~ 40-50% mass in wood
- Tensile strength up to 7 GPa
- Hydrogen bonds: ~ 0.2 eV/bond (2nd bond, biodegradable)
- > 2500 HBs per µm per molecular chain



CO_2 Impact



1.85 kgCO_2 <u>emission</u> per 1 kg steel produced.



- **~ 1.8 kg CO_2 per 1 kg <u>stored</u> in wood;**
- **1 mature tree is ~ 1 ton CO_2**

Store carbon for a long time



Bottom Up vs. Top Down in Wood Research: Focus on Cellulose Nanofibers

Cellulose is the most abundant biomaterial.







Bottom up

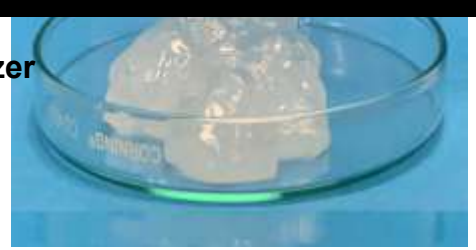


Vision:

- Upgrade fiber performance from nanoscale (beyond green)
- Maximize fiber use from forestry

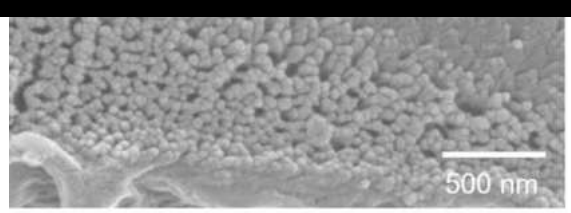


- Microfluidizer



Top down approach:

- **Manufacturing**
- **Maintain wood structure (anisotropic)**



Transparent wood

- More light (~92% transmittance; light guiding effect
- Less heat (6X lower thermal conductivity)
- Advanced Materials, 28, 5181, 2016

Insulation wood

- Low thermal conductivity ~0.03 W/(mK)
- Anisotropic behavior for better thermal management
- Science Advances, 4, eaar3724, 2018

12 mm 0.3 mm

Radiation Cooling:

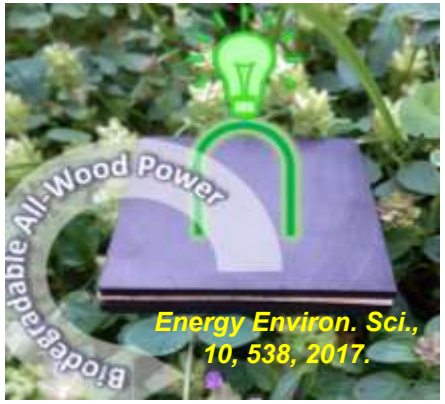
- "White" in solar spectrum
- "Black" in infrared
- Cooling power ~53 W/m^2
- Science, 2019, 364, 760

Super Wood

- 600 Mpa
- 1.3 g/cm^3
- Nature 2018



Science → Technology → Manufacturing and industry



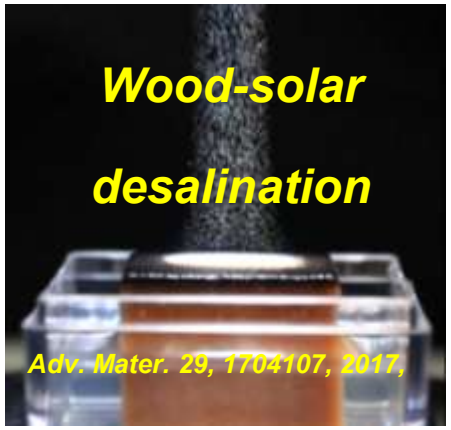
Energy Environ. Sci., 10, 538, 2017.

Solid state battery

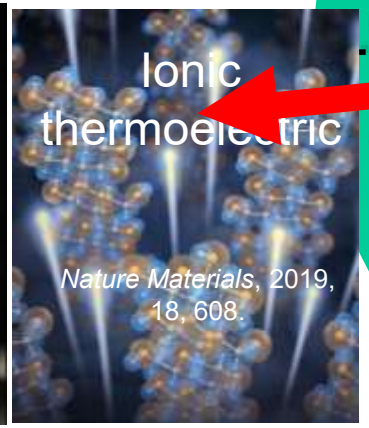


Nature, 2021

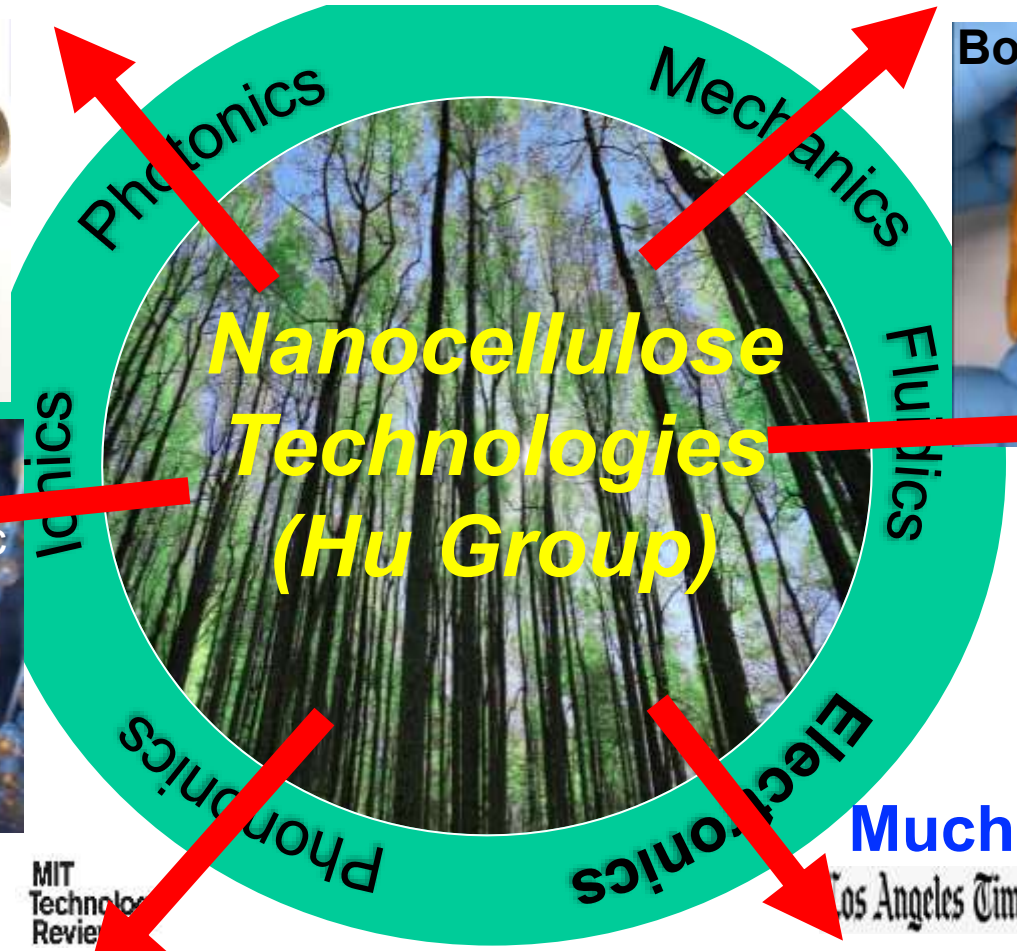
Wood-solar desalination



Adv. Mater. 29, 1704107, 2017,



Nature Materials, 2019, 18, 608.



Bouncing wood





Much more at the nanoscale!

BBC NEWS · npr news · CNN · VOA Voice of America · MIT Technology Review · Los Angeles Times · The New York Times

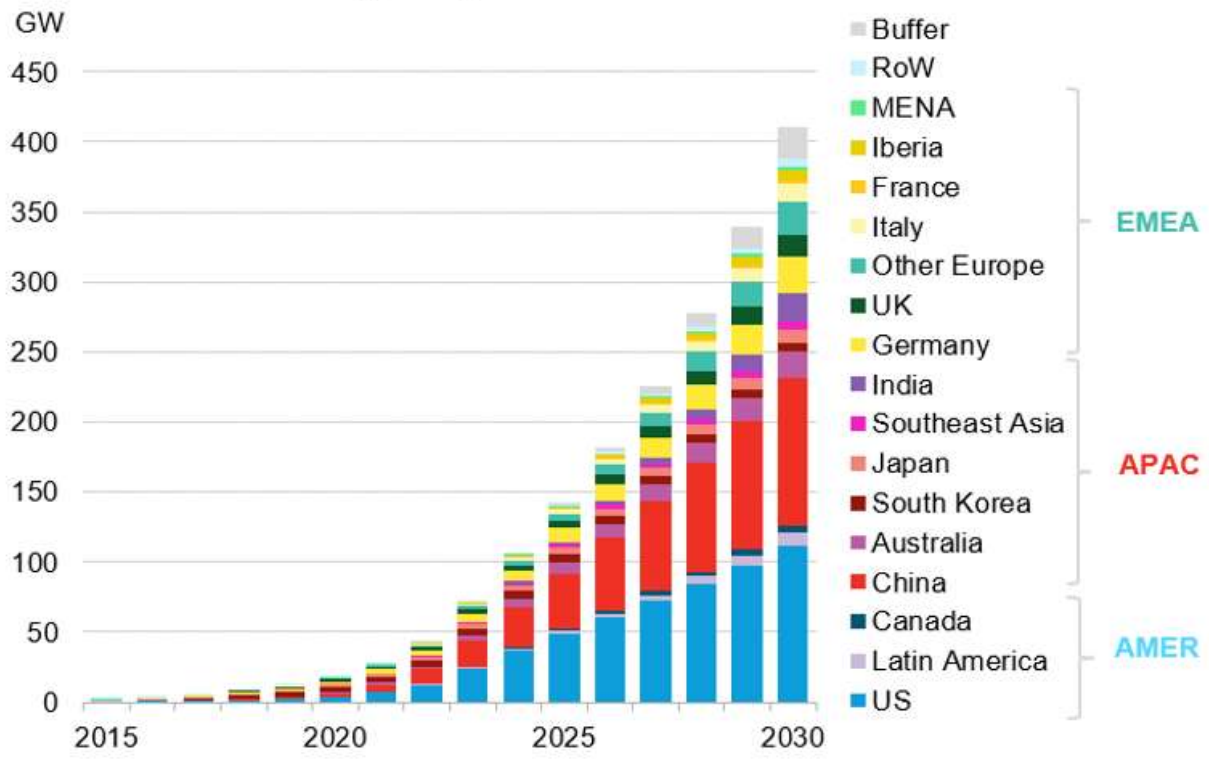
Technology 1: Wood Batteries

Molecular-Scale Engineering of Cellulose Nanofibers

Nature 598, 590, 2021

Why Important ?

Global Energy Storage Market to Grow 15-Fold by 2030



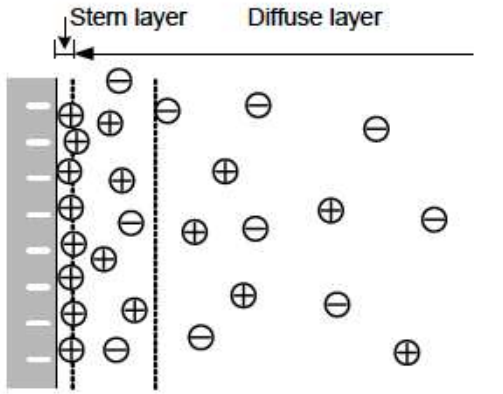
Source: BloombergNEF. Note: "MENA" refers to the Middle East and North Africa; "RoW" refers to the rest of the world. "Buffer" represents markets and use cases that BNEF is unable to forecast due to lack of visibility.

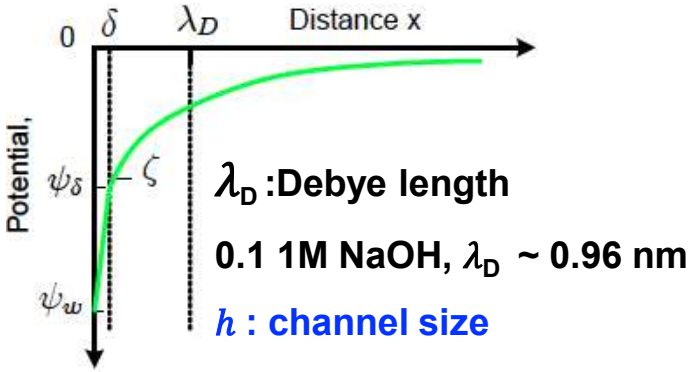
BloombergNEF Report:

2030, ~ 400 GW
15X of 2021

BloombergNEF (BNEF) is a strategic research provider covering global commodity markets and the disruptive technologies driving the transition to a low-carbon economy.

Ion Transport in Nanosized Channels

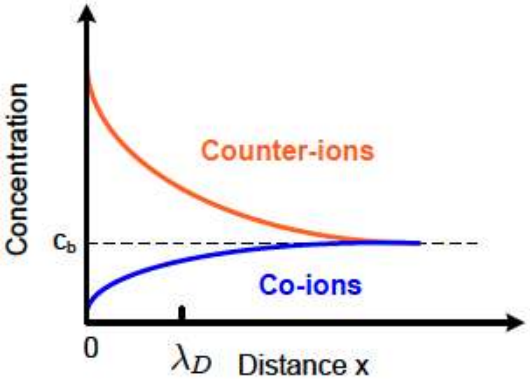




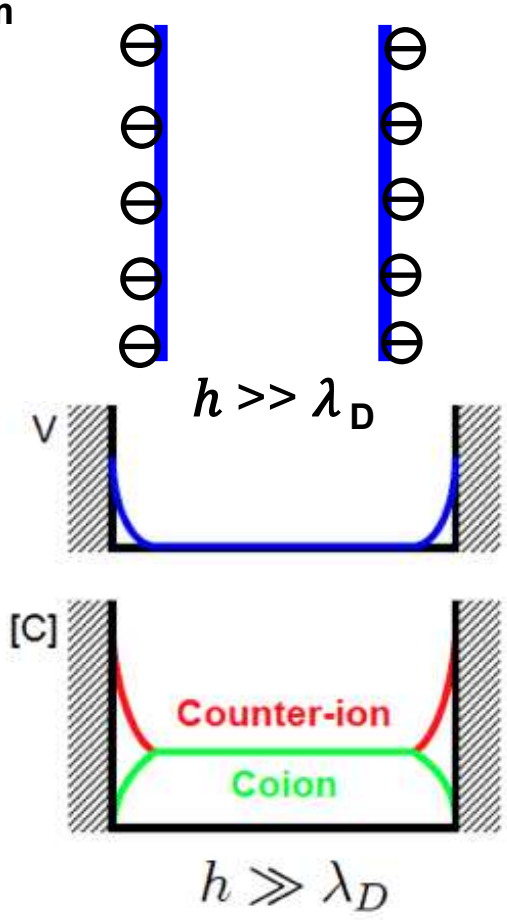
λ_D :Debye length

0.1 1M NaOH, λ_D ~ 0.96 nm

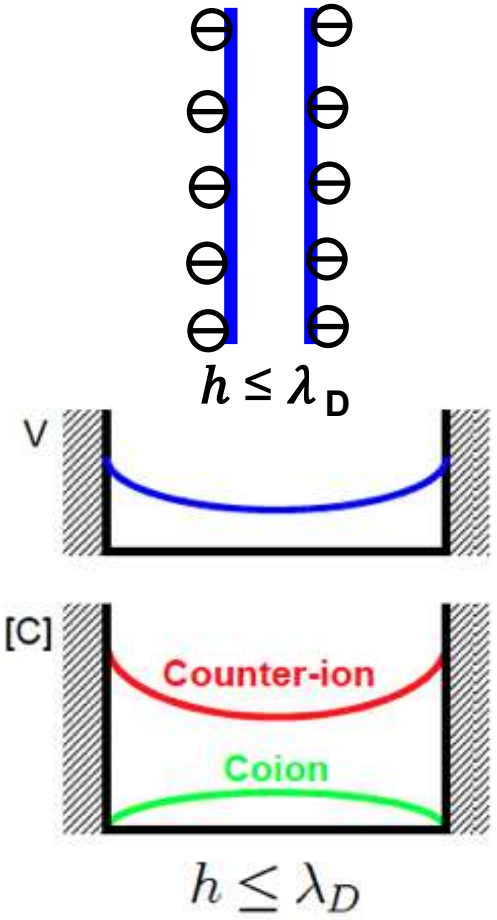
h : channel size

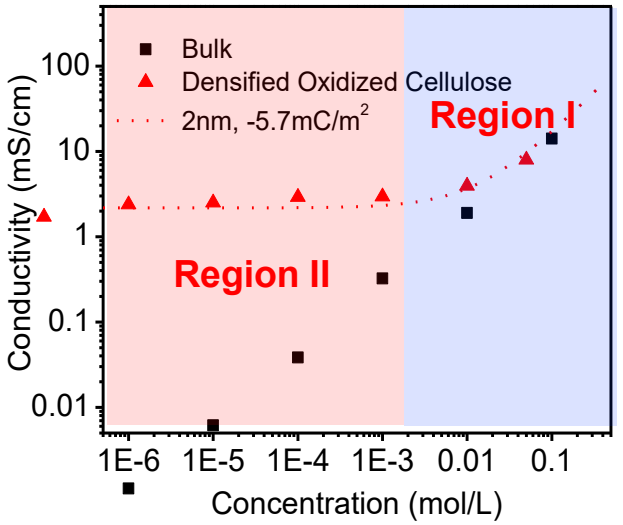


Bulk behavior: Typically $h \geq 100$ nm



Nano-behavior: Typically $h \leq 10$ nm





$$\lambda_D = \sqrt{\frac{\epsilon_0 \epsilon_r kT}{2z^2 qF c_b}}$$

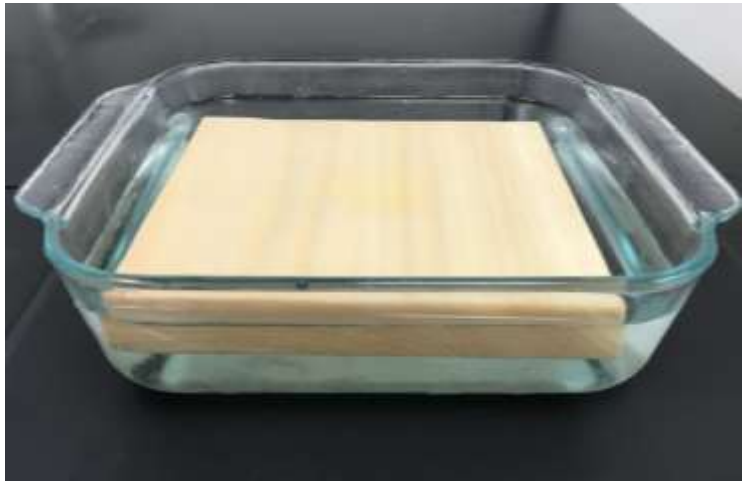
Bulk behavior:

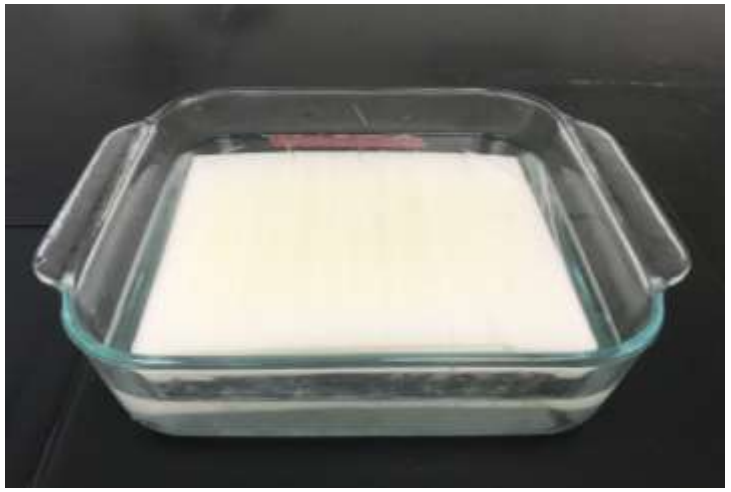
- High concentration (small λ_D)
- Microsized channel

Nano-behavior (Small channel or low concentration C_b) :

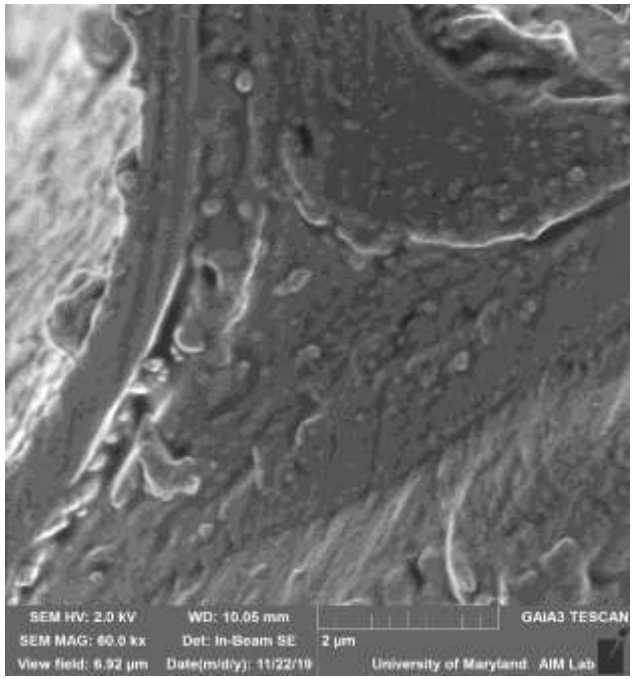
- Surface charge governs the ion concentration inside the nanochannel (ion selectivity)
- **Constant conductivity vs. concentration**

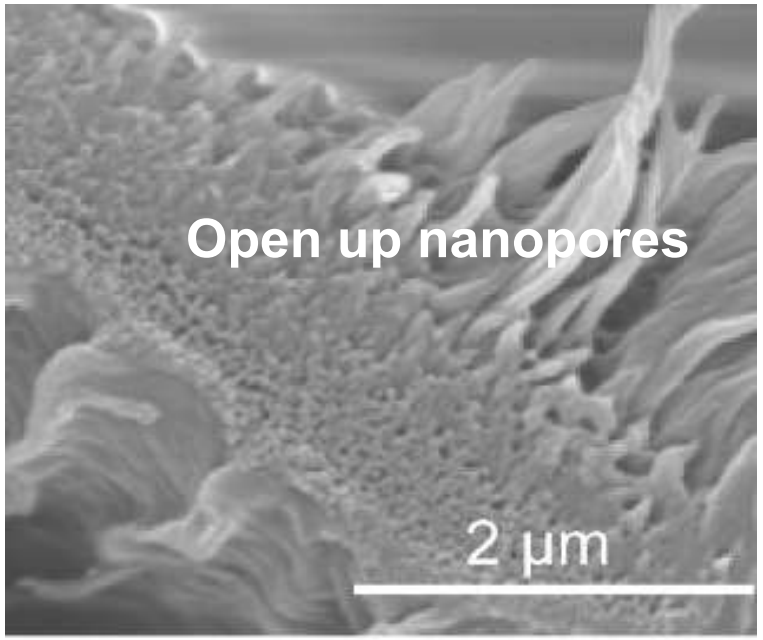
Completely Delignification Opens Up Nanochannels





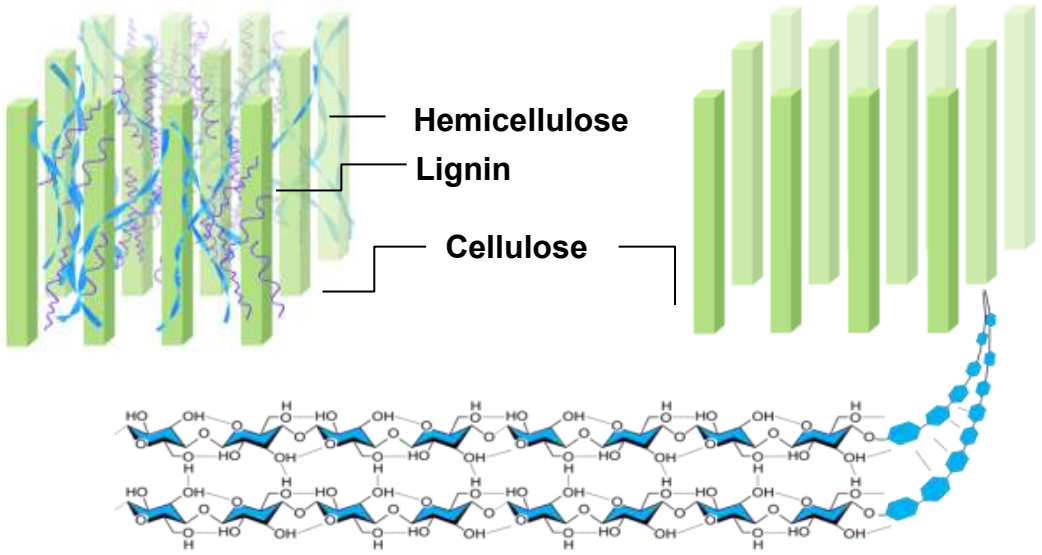
Complete delignification

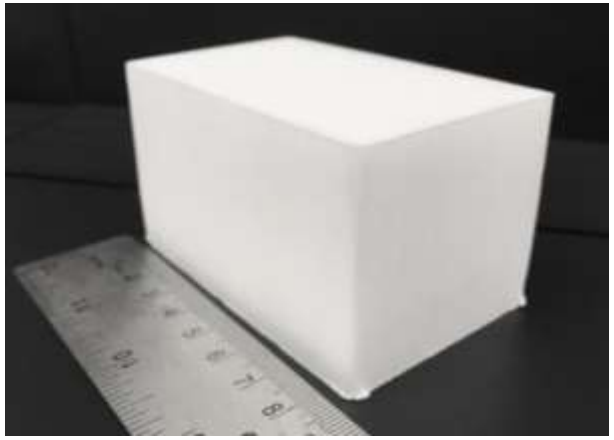


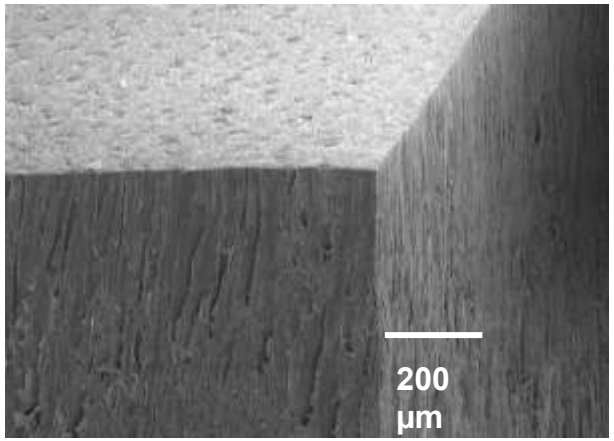


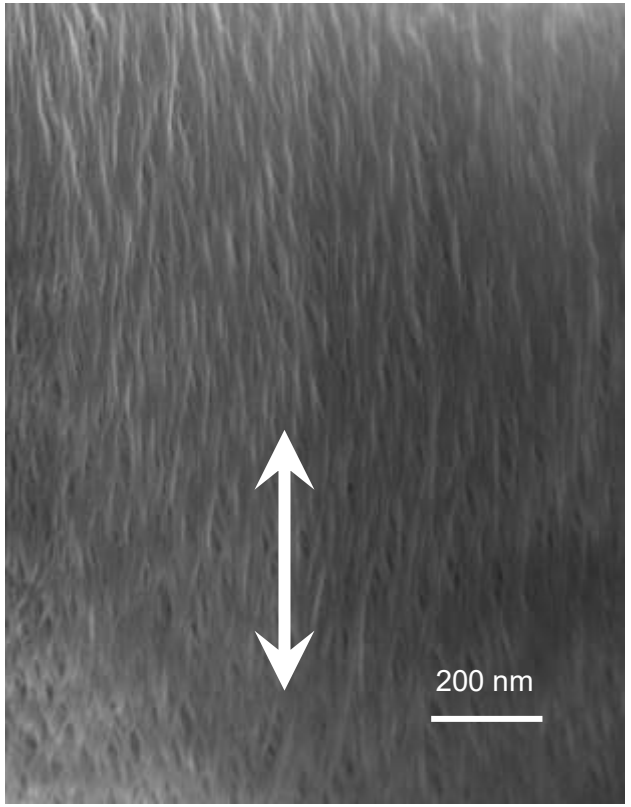
Nature Materials, 2019, 18, 608.

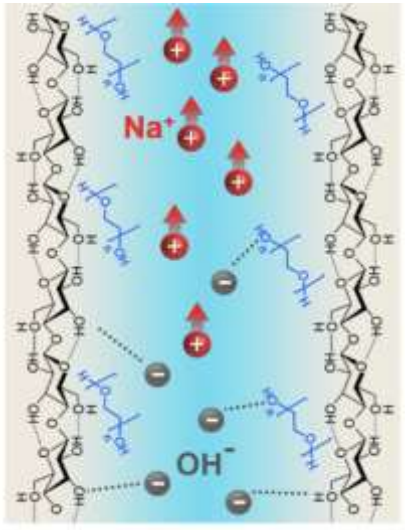
Completely Delignified Wood as 3D Ionic Membrane











- Removal of intertwined lignin and hemicellulose;
- Preserve the alignment;
- Abundant surface functional group.

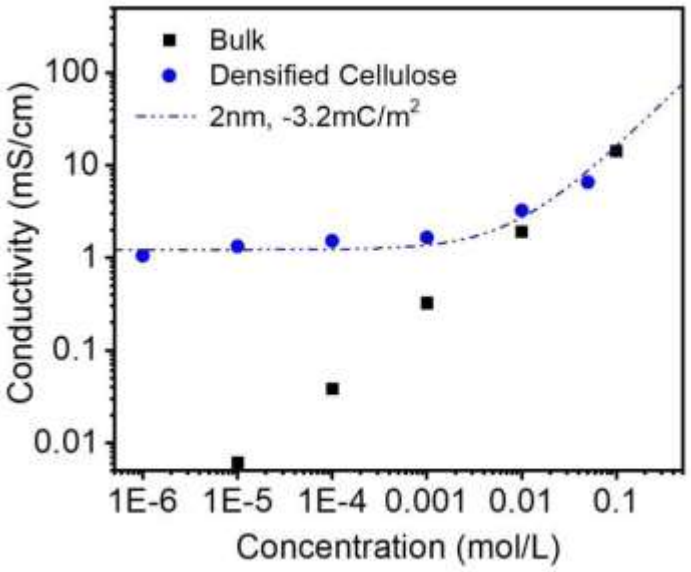
Unique!!!

- **Bulk membranes with aligned fibers**
- **Charge selectivity**

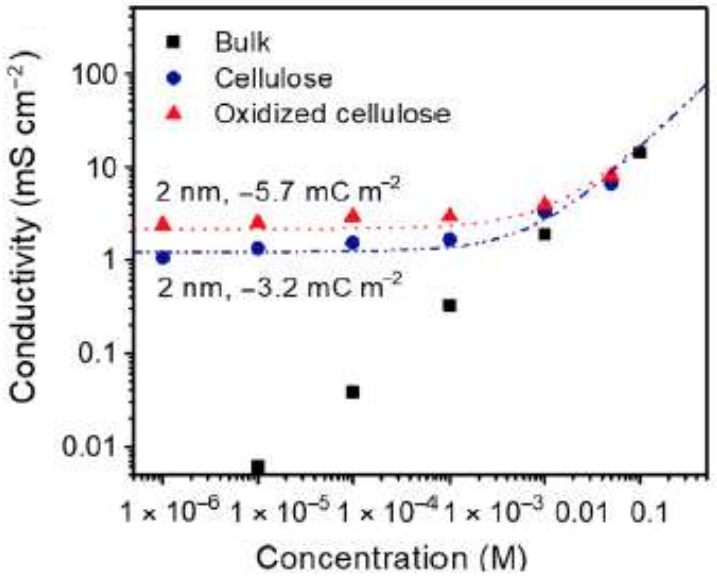
Nature Materials, 2019, 18, 608.

Ion Transport in Wood with Aligned Cellulose Fibers

Cellulose

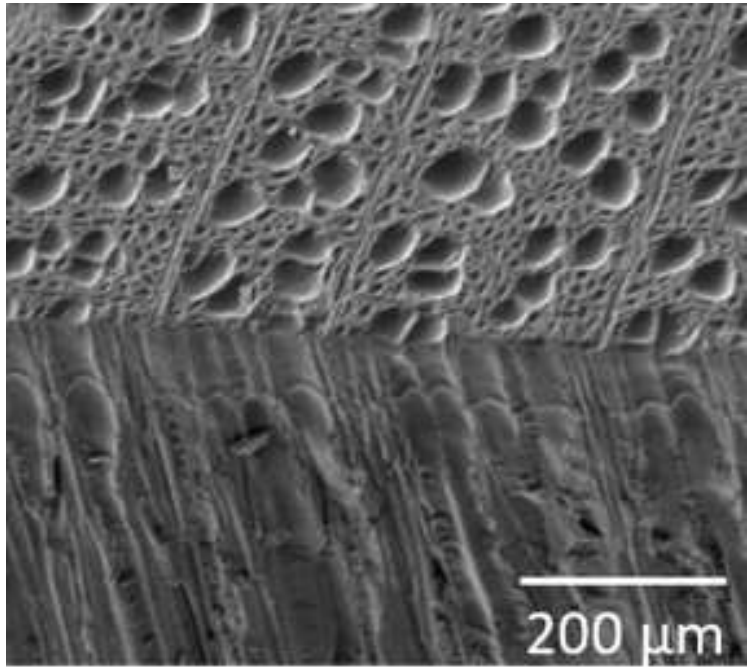


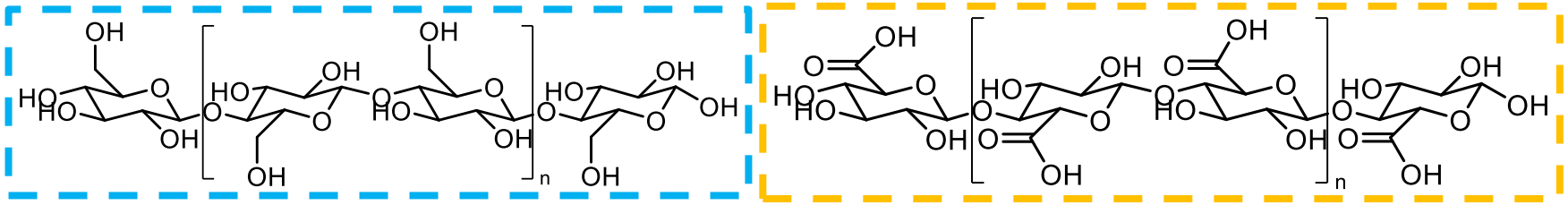
Oxidized Cellulose



Remove Large Channels for Charge Selectivity

- Press to remove large channels;
- Fill large channels with polymers.





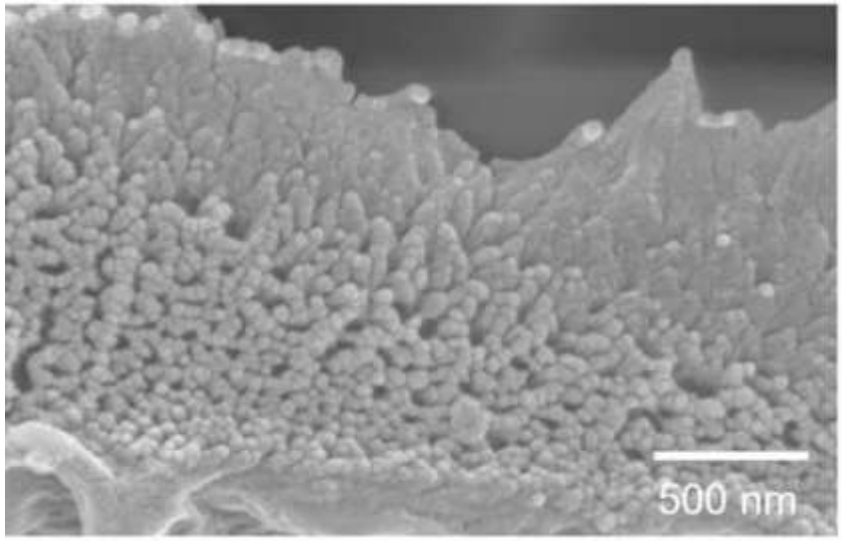
Nano-channels are the key!

- TEMPO oxidation converts hydroxyl groups to carboxylate groups (largely increase the surface charge of cellulose nanofibers).

Nature Materials, 2019, 18, 608.

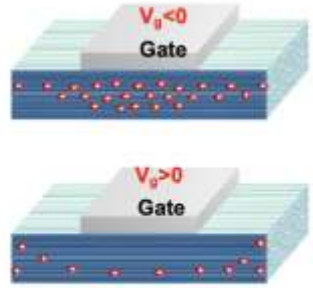
Devices on Ions (Nanofibers in Wood or Paper): Batteries, Bio, Clean Water

Cellulose nanochannels



- **Ion selectivity**
- **Fast ion transport**
- **Mechanical strength**

Ionics (vs. electronics)



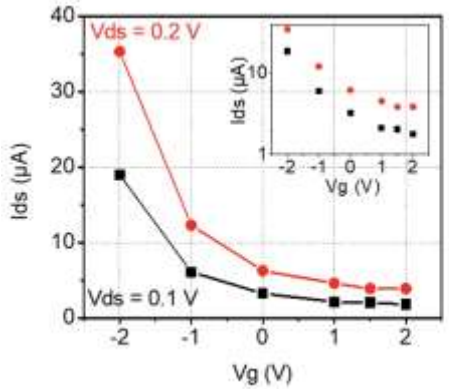
- **Ion generator for biotech**

  (Nature Comm. 8, 15609, 2017)

- **Ionic diode**

  (Science Advances, 2019)

- **Ionic circuit**



Energy harvesting

(Nature Materials, 2019)

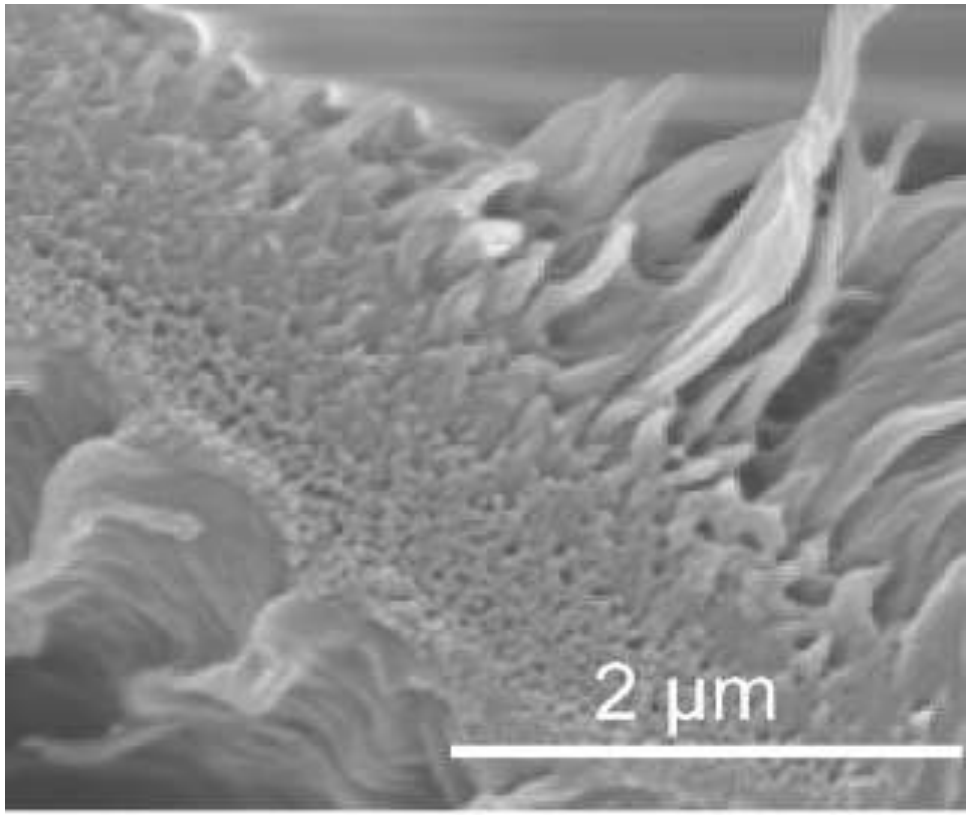
Water Treatment

(Science Advances 2021)

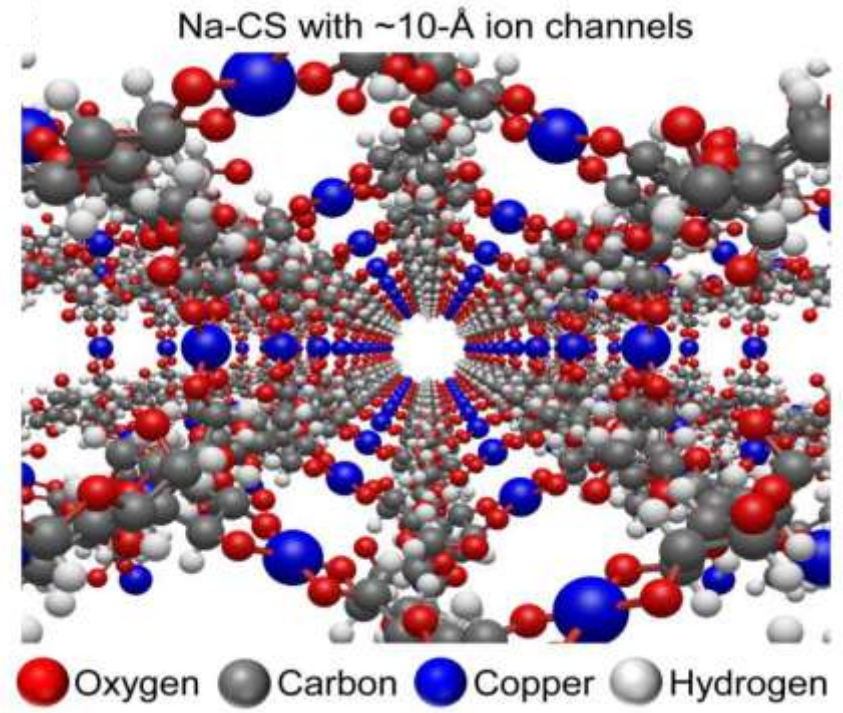
High performance batteries

(Adv. Energy Mater., 2018, 8, 1802398)

Corrosion protection



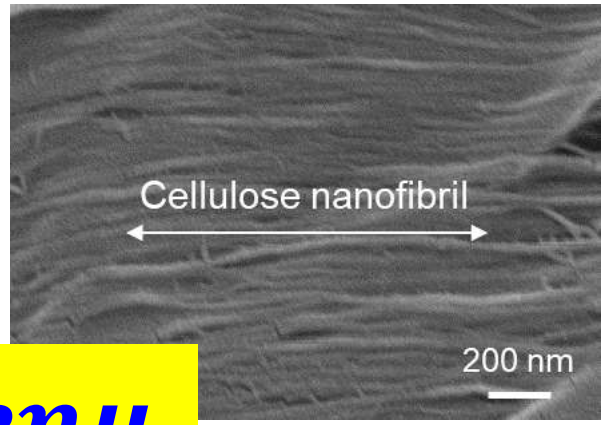
***Nanoscale* engineering *among* cellulose nanofibers**



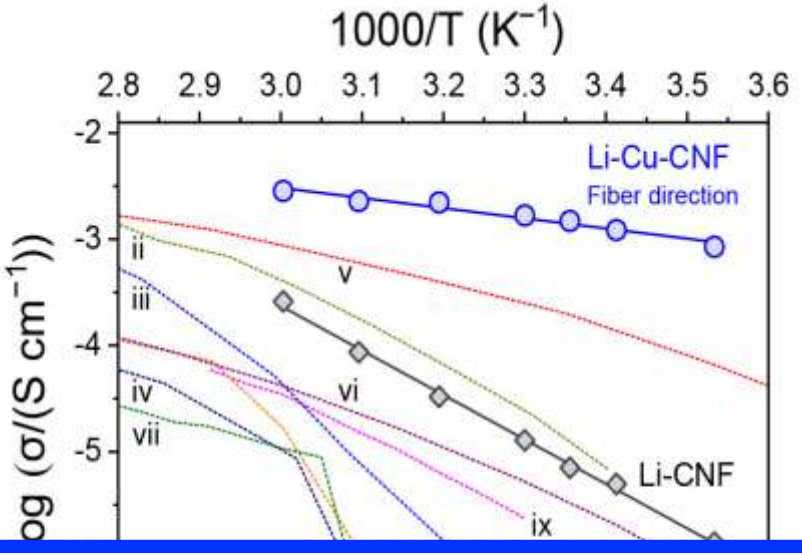
***Molecular* engineering *within* cellulose nanofibers**

Intercalated Nanofiber: Opening Up Molecular Channels





$$\sigma = en\mu$$



University of Maryland – College Park, MD

Fast-Charging, Solid-State, Roll-to-Roll Processed Li Metal Batteries Enabled by Intercalated Ions in Cellulose Molecular Channels - $2,600,000

PI Liangbing Hu, ARPA_E OPEN announcement, 2/20/2022

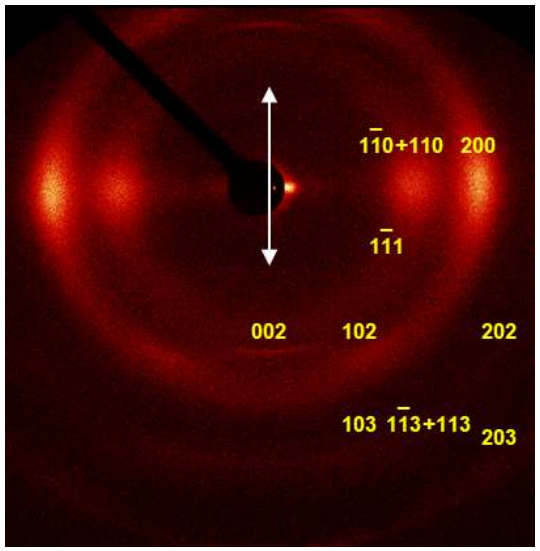
The University of Maryland (UMD) team seeks to fabricate fast-charging batteries in which the electrolyte comprises a cellulose fiber-based ion conductor. The cellulose-based ion conductor overcomes the gap from current solid-state electrolytes to solid-state batteries because they use natural materials, are easy to process and are compatible with conventional coating processes. UMD's approach could enable high conductivity at room temperature, high energy density, and roll-to-roll manufacturing of nano-paper batteries with low cost. UMD's cellulose-based batteries will be capable of empowering electric vehicles (EV) with high energy and fast charge, promoting U.S. leadership in the EV market.

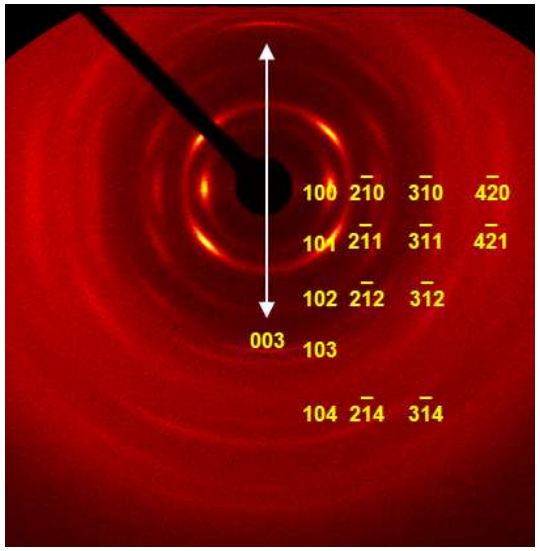
Cu^{2+}-CNF Coordination (Expanded Structure)

CNF → Cu-CNF-NaOH

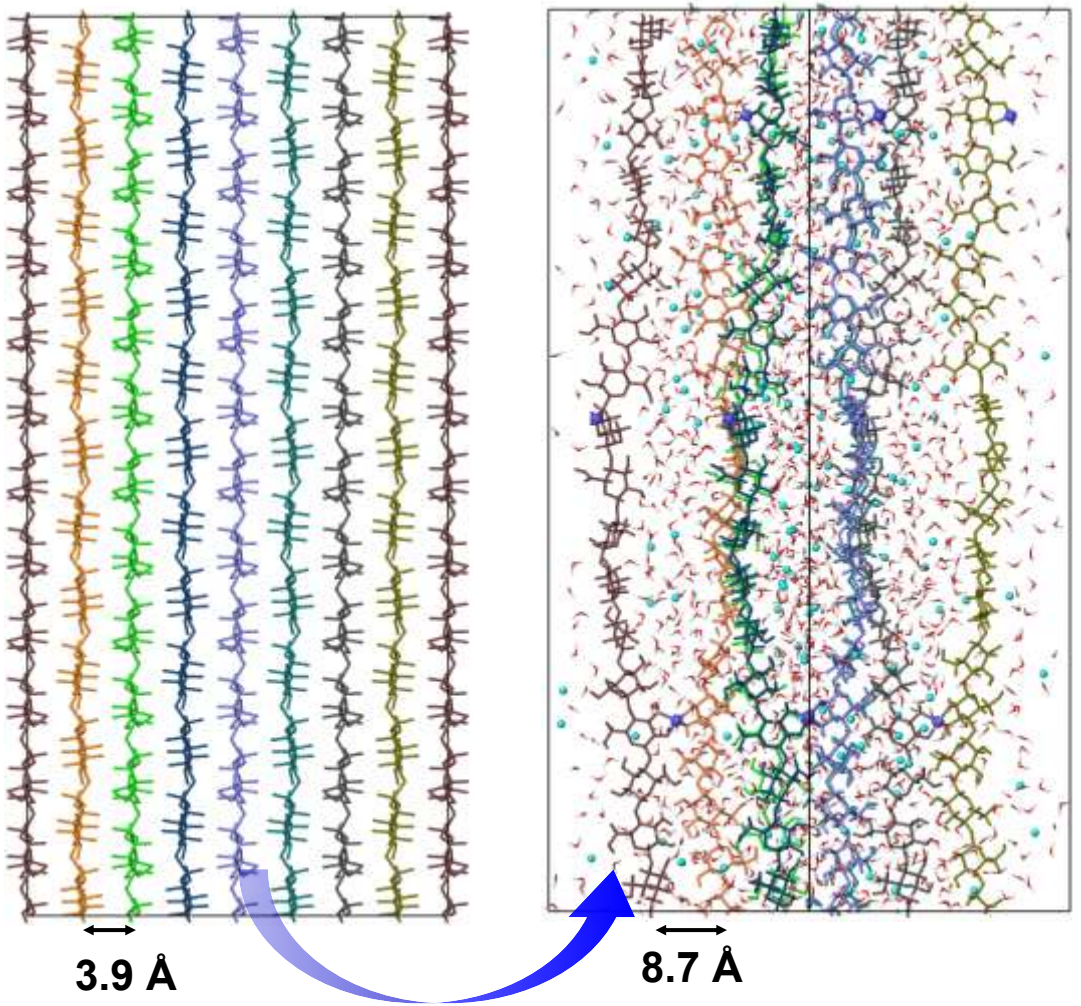








CNF Cu-CNF-NaOH

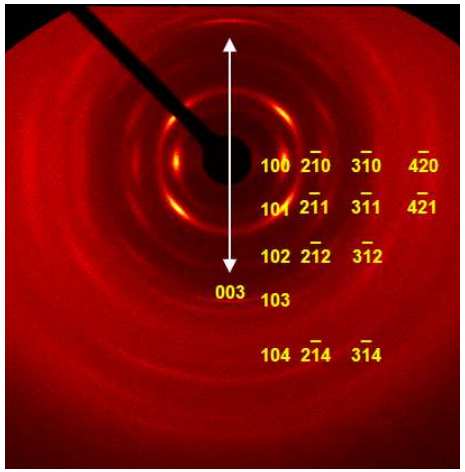


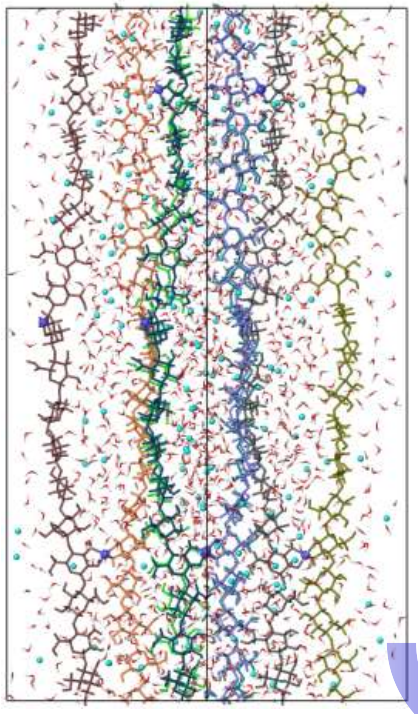
Cu^{2+} coordination by ion/solvent exchange, opening the cellulose molecular spacing

Crystalline to Amorphous

Crystalline, wet Cu-CNF





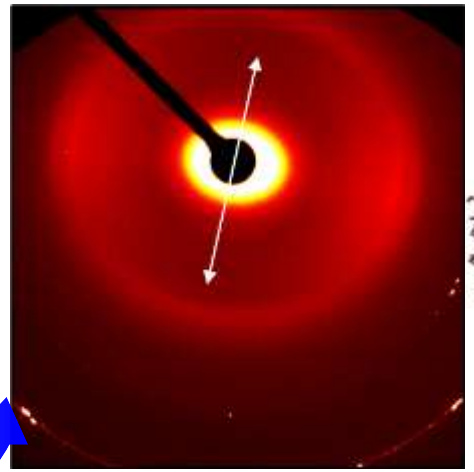


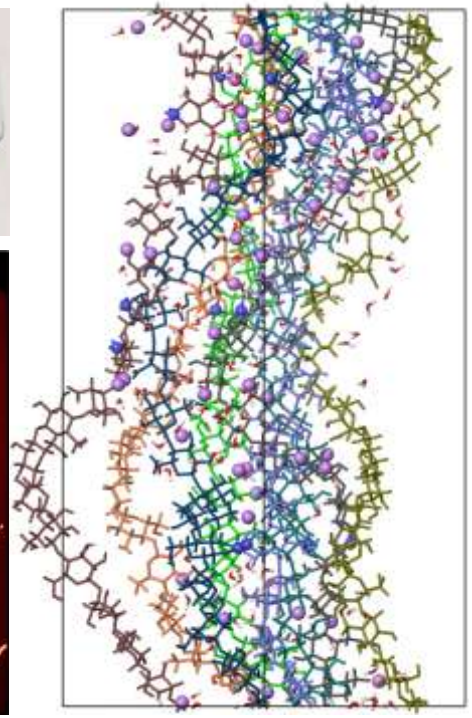
- Crystalline, MOF structure
- Open spacing
- ~ 1 nm ordered nanochannels

- Solvent exchange
- Water displacement
- Li^+ insertion

Amorphous, solid-state Li-Cu-CNF

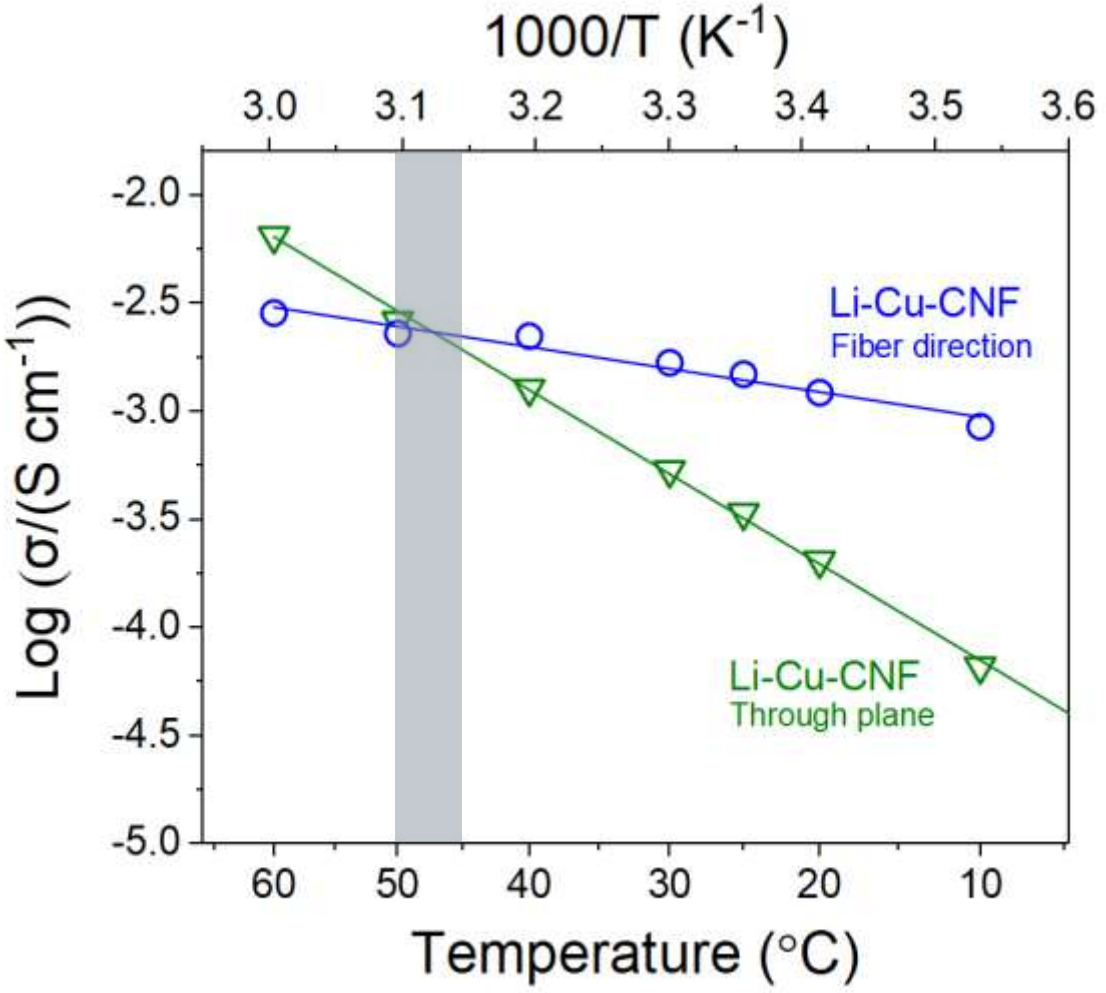






- Amorphous, solid-state electrolyte
- Open spacing
- Nanochannels
- Bound water

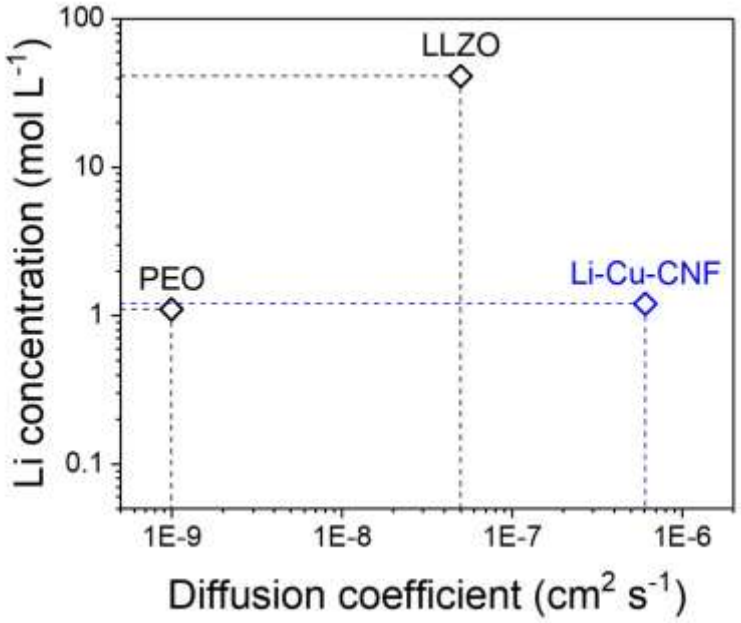
High Ionic Conductivity by the Dry Cellulose Nanofibers



Low activation energy (0.19 eV)

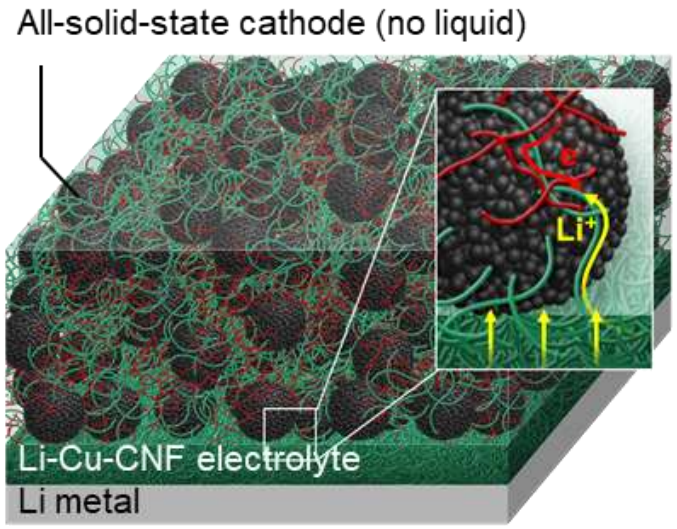
$$\sigma = enu$$

- Lower Li content (~1.2 mol/L, vs. ~40 mol/L in LLZO) for low cost.
- Higher Li^+ mobility (diffusivity)



Ionic conductivity through plane: 0.34 mS/cm at room temperature.
At 45-50 ℃, ~2.3 mS/cm, enabling fast charge/discharge in batteries.

Two Critical Applications of Li-Cu-CNF in Solid Batteries

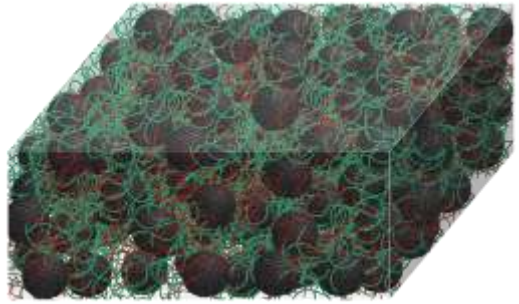


1D Li-Cu-CNF ion conductor

- **Nanopaper SSE**
  - **Dense, thin, highly conductive**
  - **Stable against Li anode and cathodes**

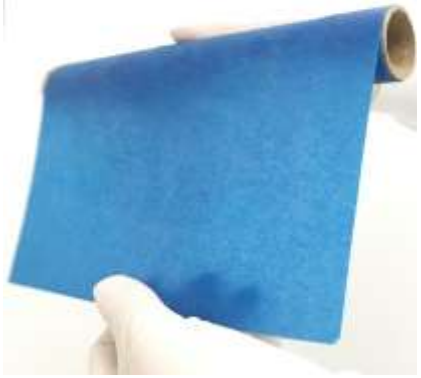


- **Ion-conducting additive**
  - **1D fiber conductor for ionic percolation**
  - **Compatible with traditional slurry coating**

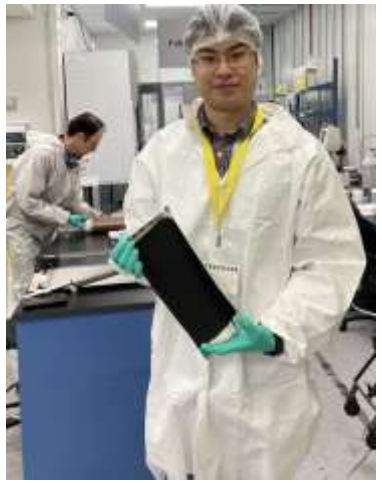


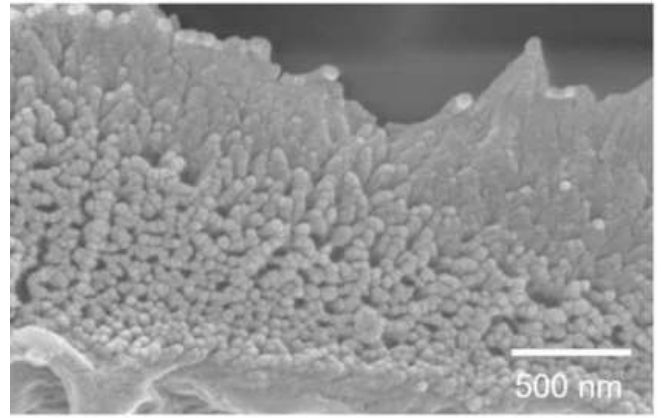
Solid-State Batteries and Manufacturing

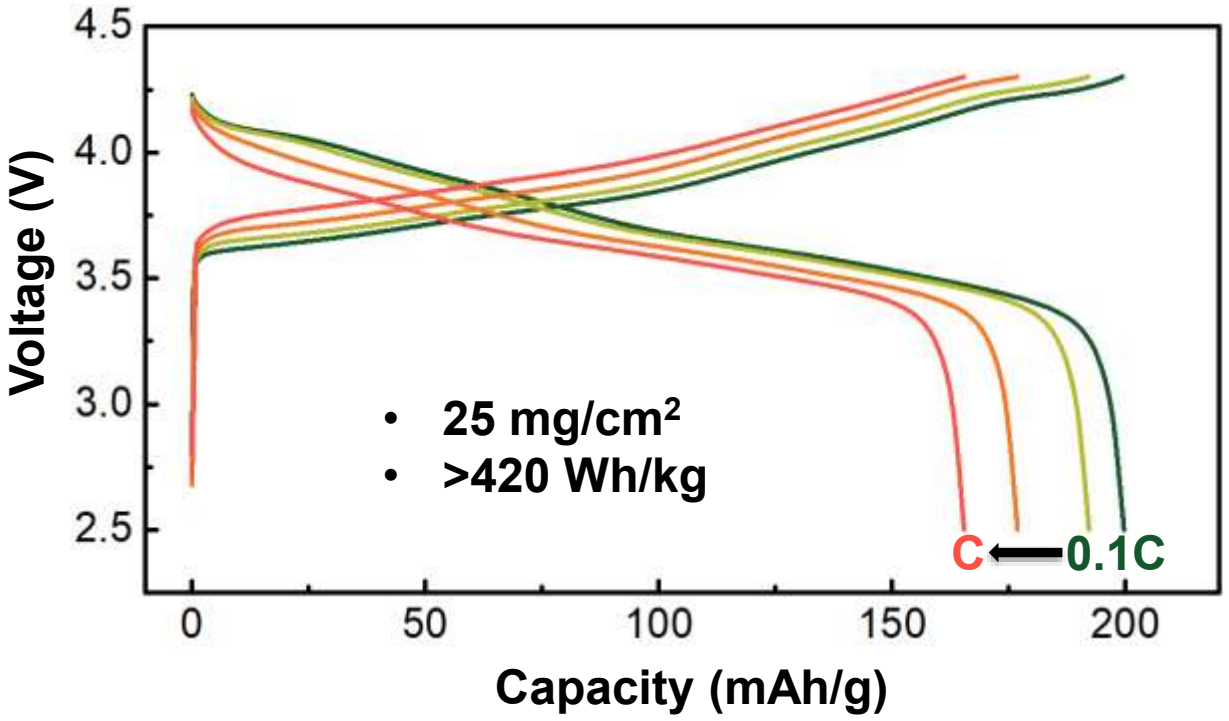
Solid-state electrolyte:
Conductivity ~1 mS/cm @RT

















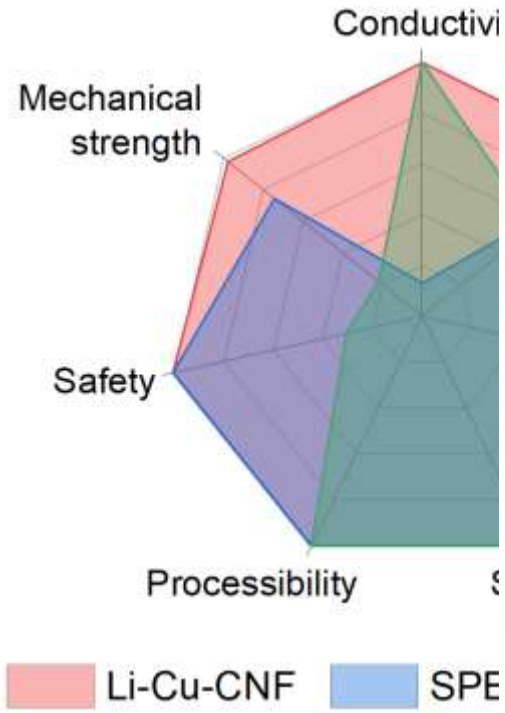
Qi Dong
Now Purdue U.

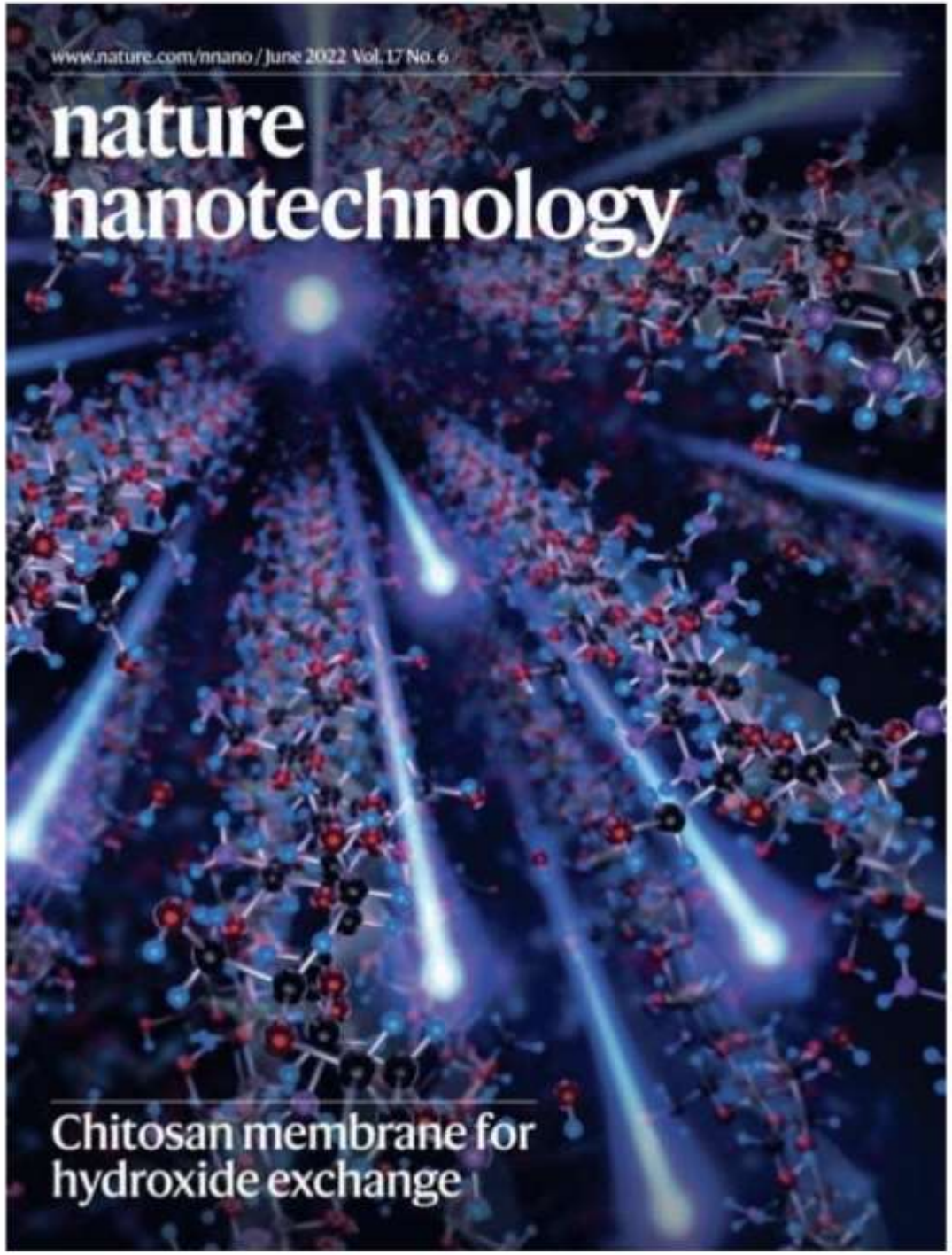


Dr. Lin Xu
(PhD, MIT)

- **Aqueous ion conductor**
- Battery for Grid and data centers

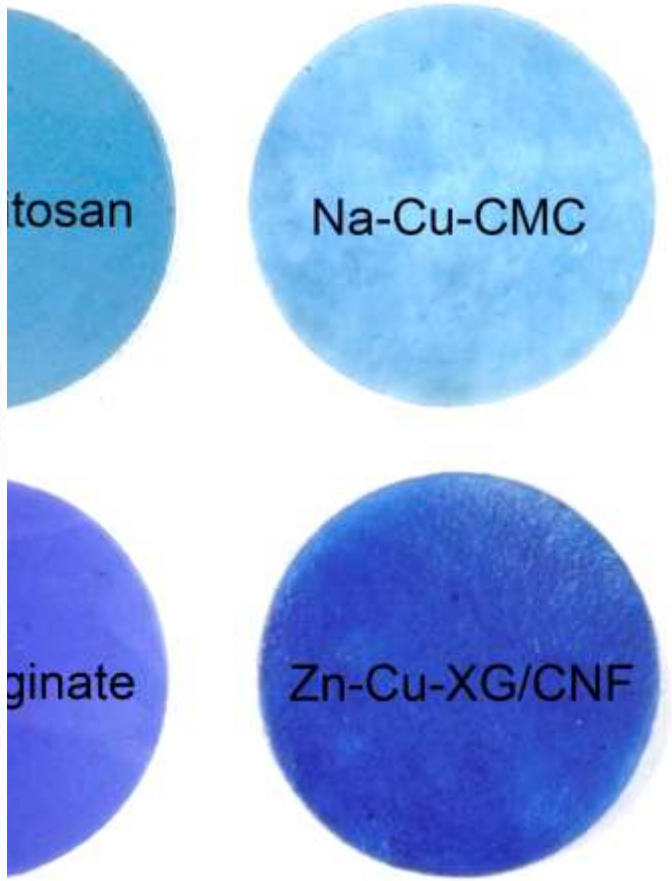
E





Ions

to other polymers and cations



Commercialization Effort: WH-Power Inc

www.wh-power.com



USDA Forest Product Lab



Technology 2: Super Wood

Revolutionize Timber Industry through Nanotechnologies

Nature, 2018, 554, 224, 2018; Science, 374, 465, 2021

Densified Wood to Replace Steel

Skyscraper



~ 7% CO_2 emission is for steel production
~ 60% steel is used for buildings

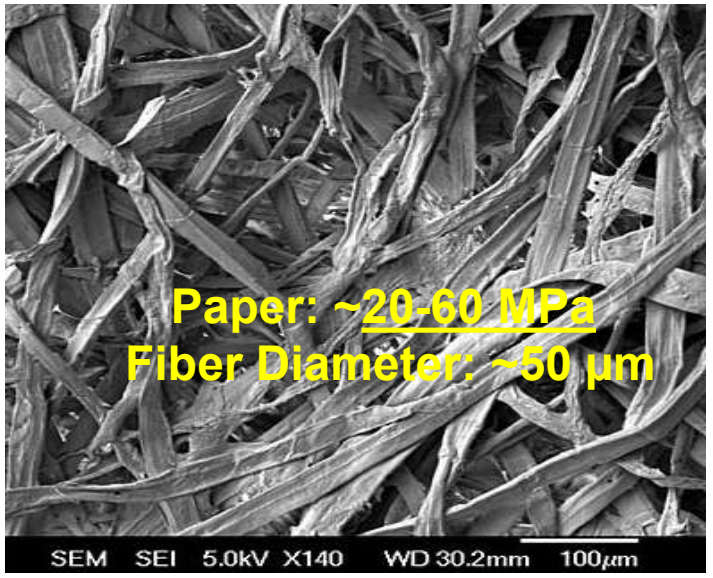


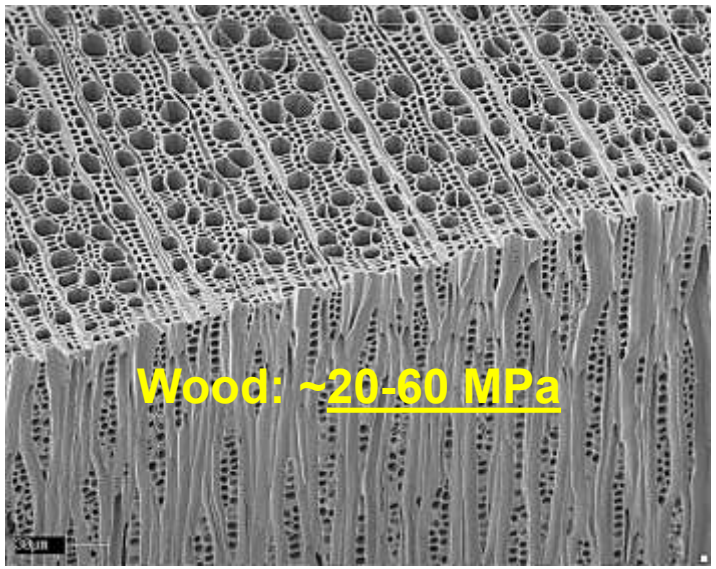


www.naturallywood.com

Limited Performance of Wood/Paper, and Great Potential of Cellulose Nanofibers

Pores are mechanical defects!



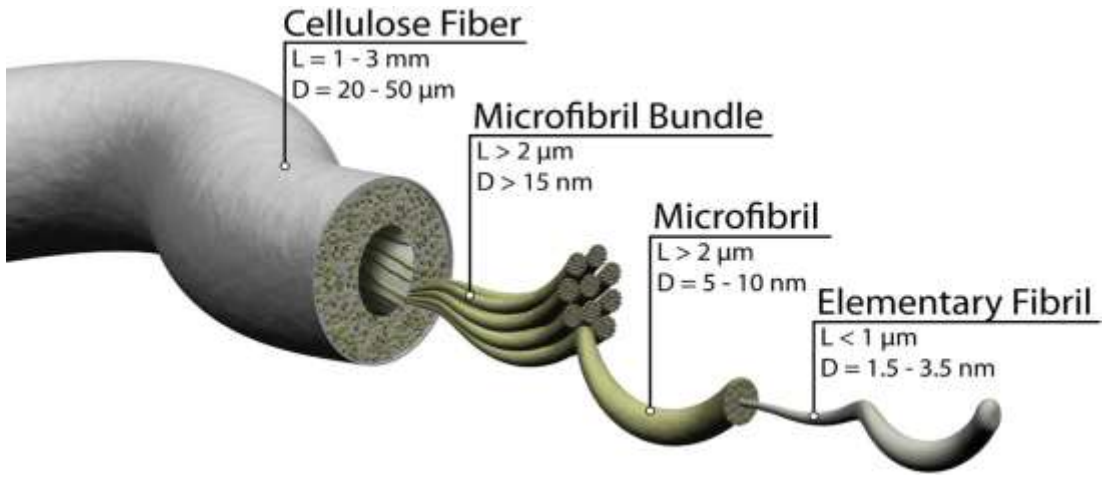


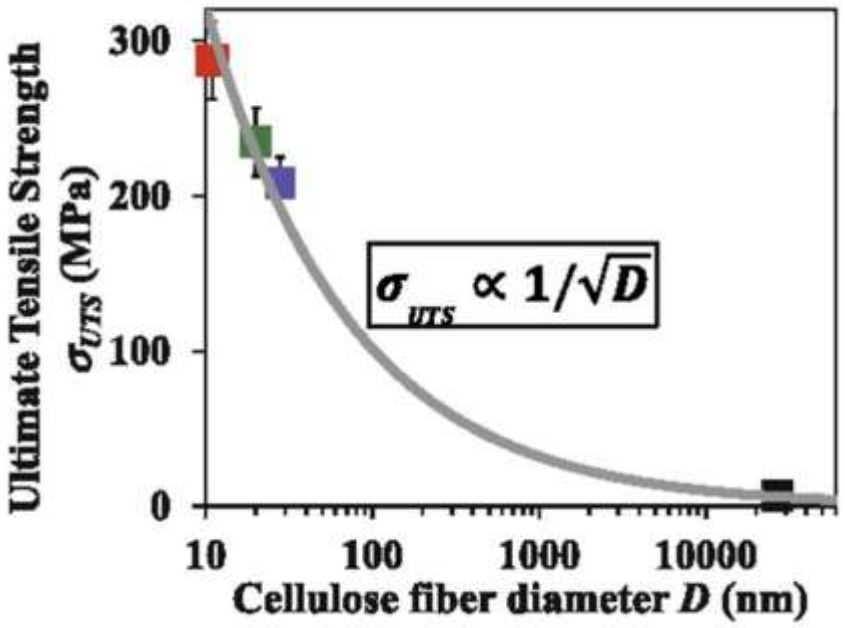
Cellulose nanofibers:

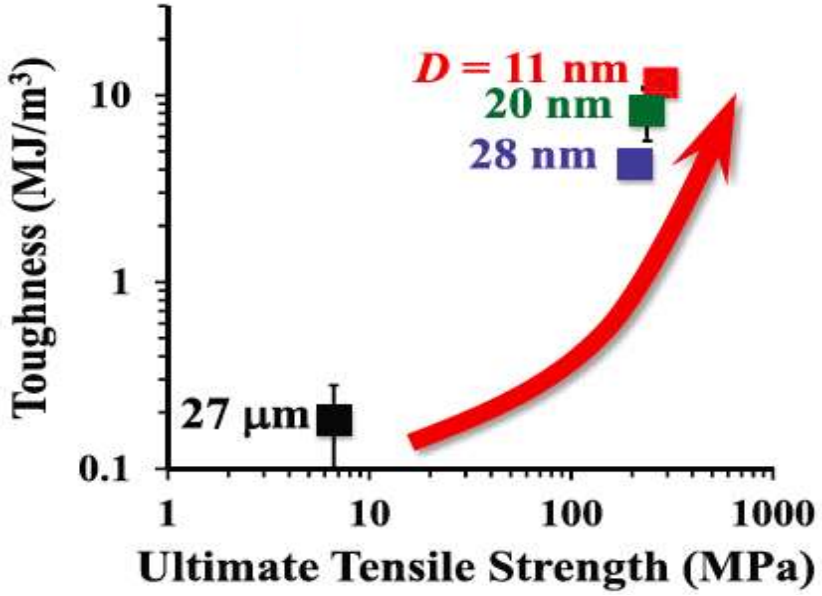
- Most amazing dielectric nanomaterials
- ~40% mass in wood;
- D ~ 10 nm;
- Tensile strength up to 7 GPa;
- Hydrogen bond: 0.285 eV/bond;
- 2727 per μm per molecular chain.

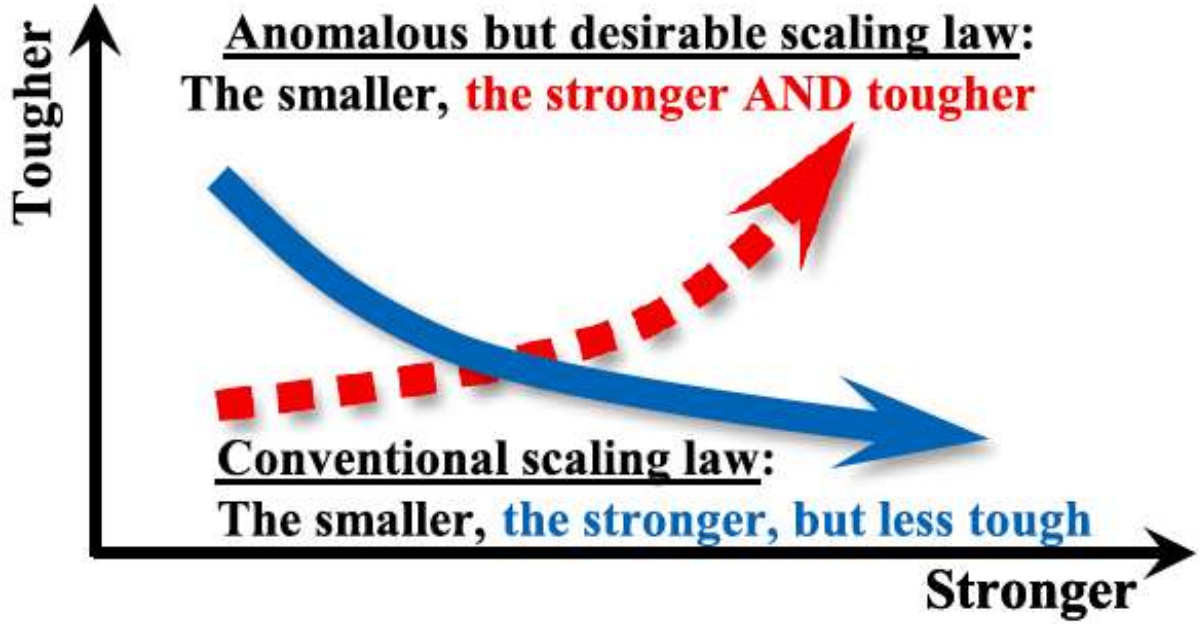
Can we make high-performance structural materials that is strong/tough and at the same time is also biodegradable in the right environment.

Scaling Behavior with Diameter: The Smaller, the Stronger



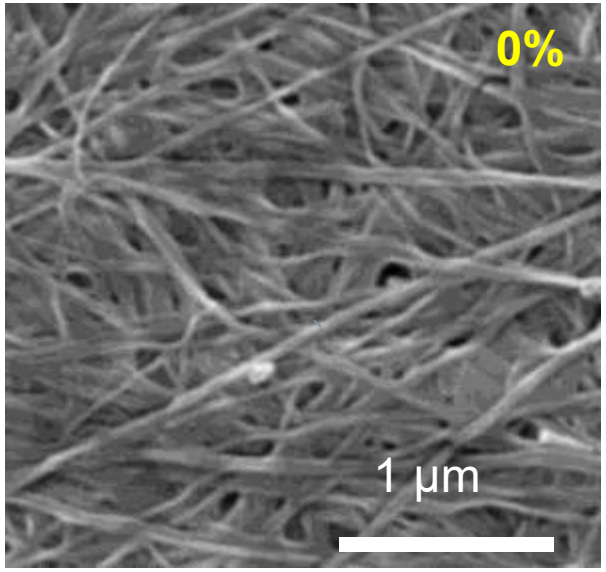


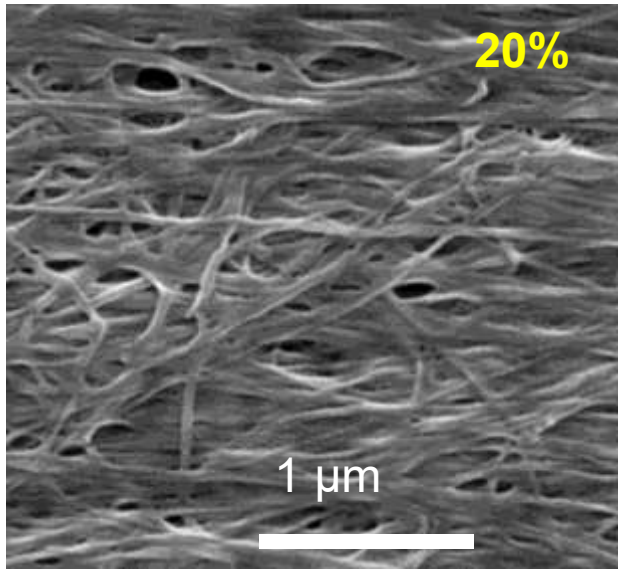


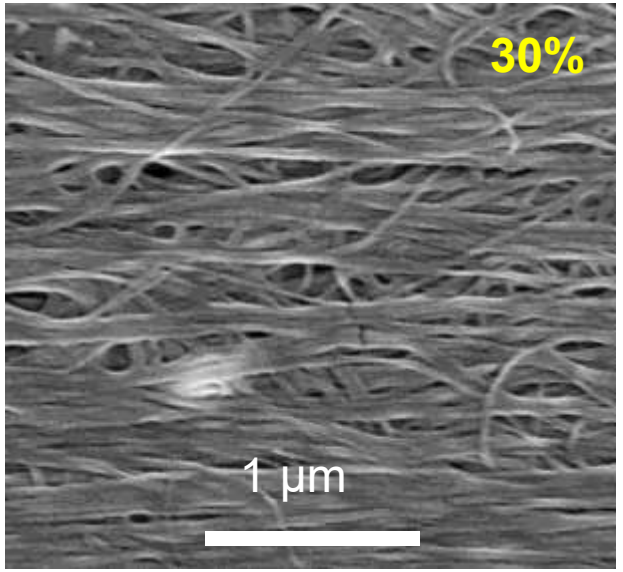


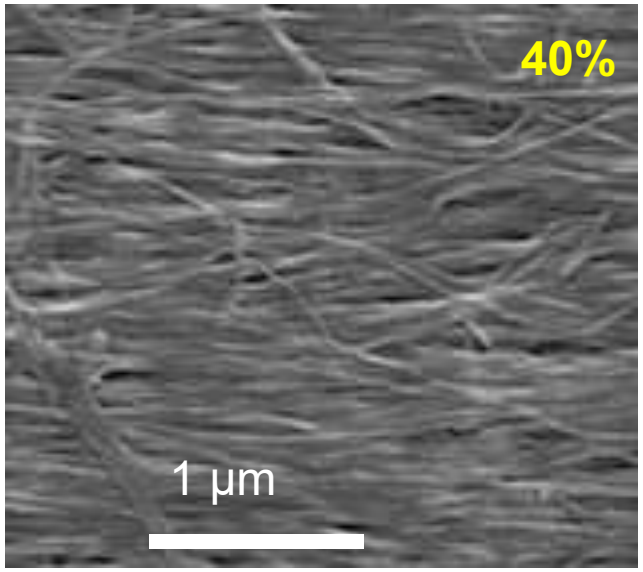
PNAS, 2015, 112, 8971

Scaling Behavior with Alignment

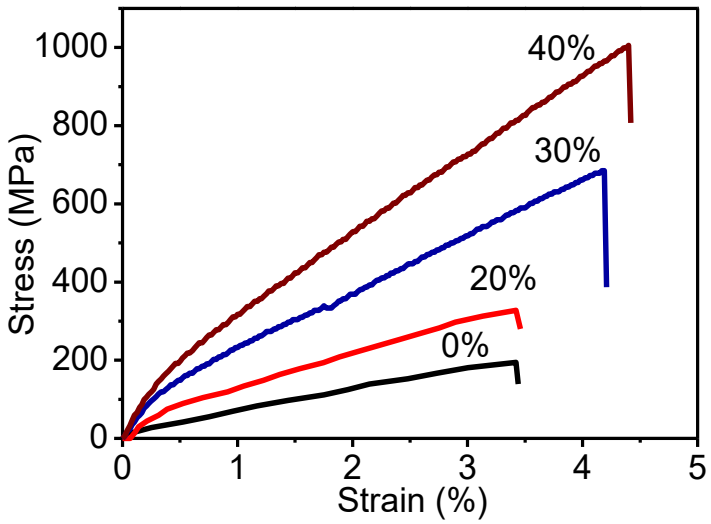




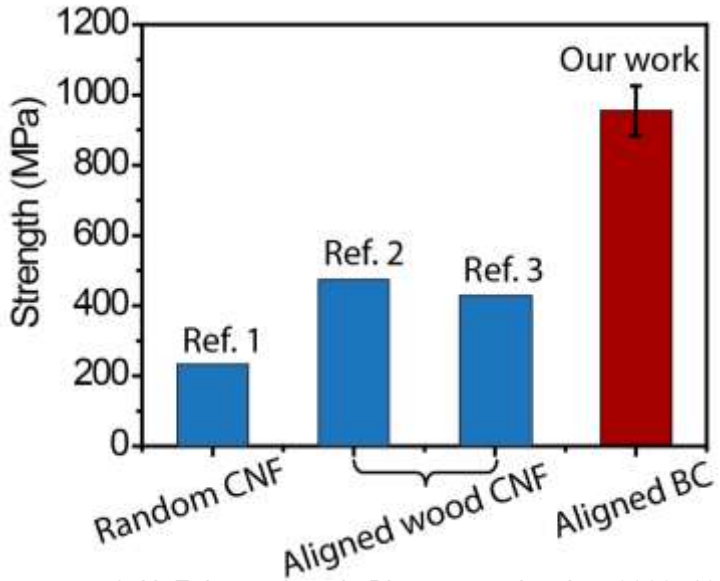




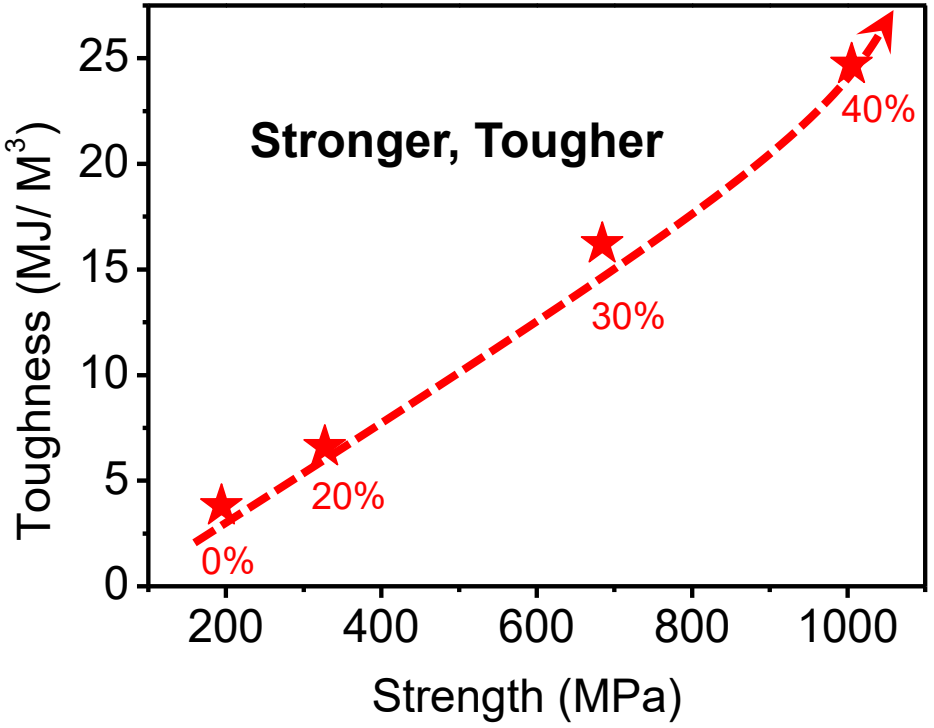
Stretch long bacteria nanofibers for alignment



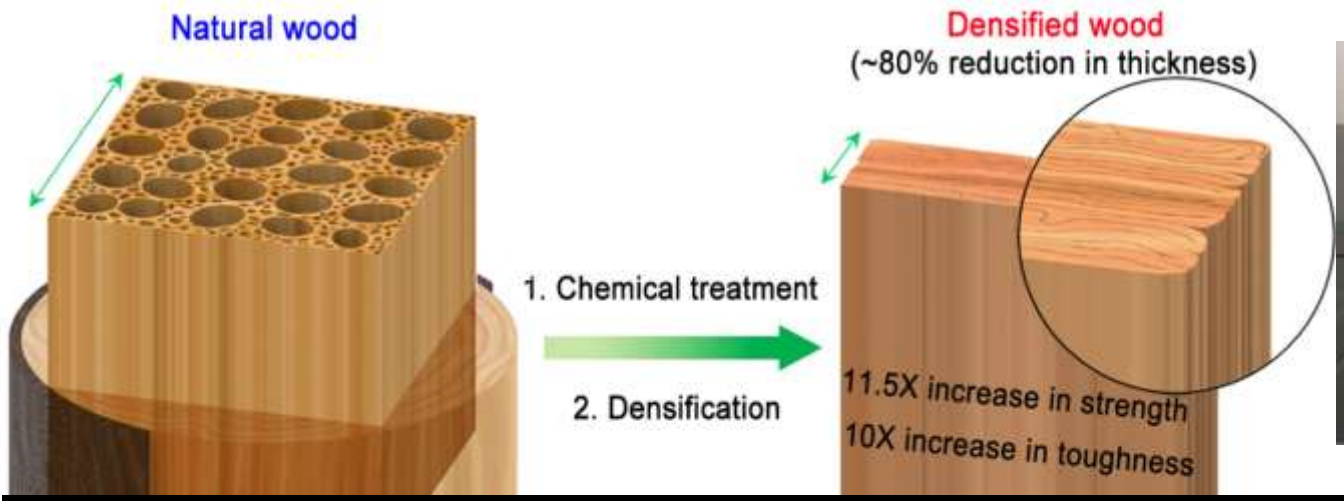
Advanced Functional Materials, 28, 1707491, 2018



1. H. Fukuzumi et al, Biomacromolecules, 2008 ,10, 162
2. C. Baez et al, Cellulose2014, 21, 347
3. H. Sehaqui et al, ACS Appl. Mater. Inter., 2012, 4, 1043



Densified Superwood (with Naturally Aligned Nanofibers)





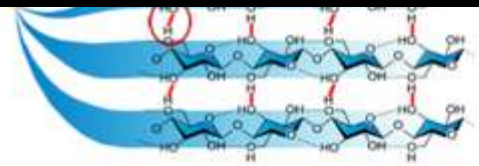
Delignification



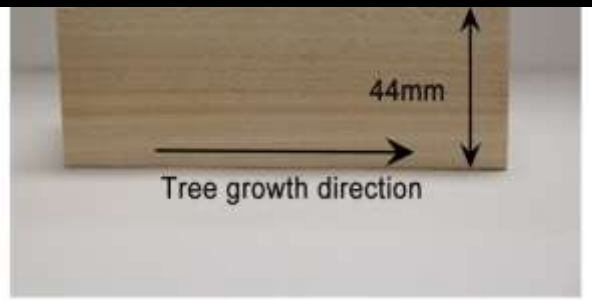
Different with other densified wood:

- **100% wood (only minimal surface coating, no bulk infiltration)**
- **High performance (tensile strength is up to 1.2 GPa)**

- **Strength is ~600 Mpa (then), ~ 1200 Mpa (now)**
- **Similar strength to steel with 1/6 density**



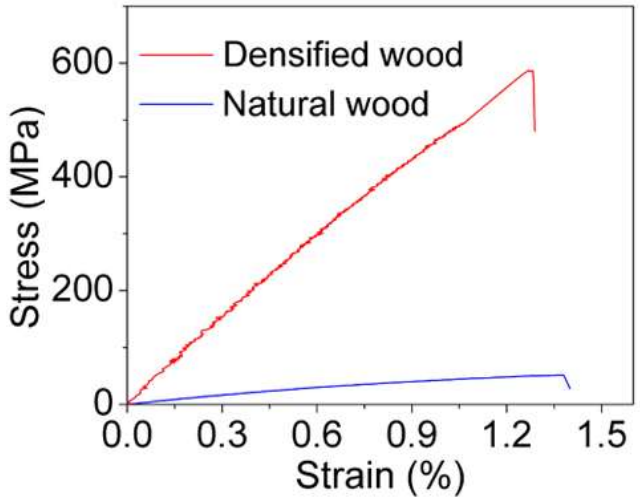
Cellulose molecular chain

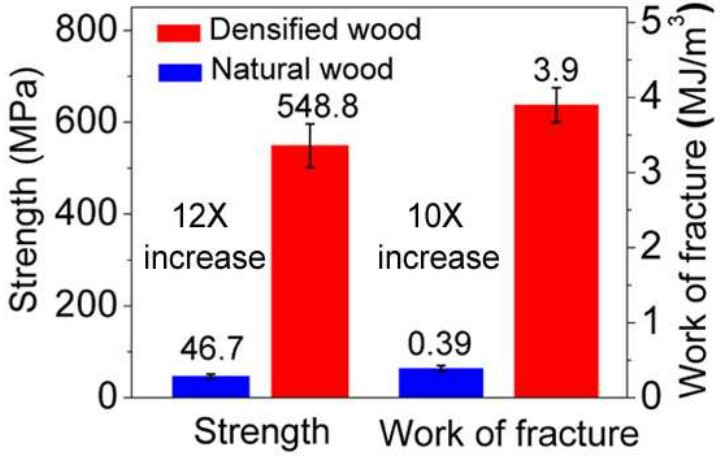


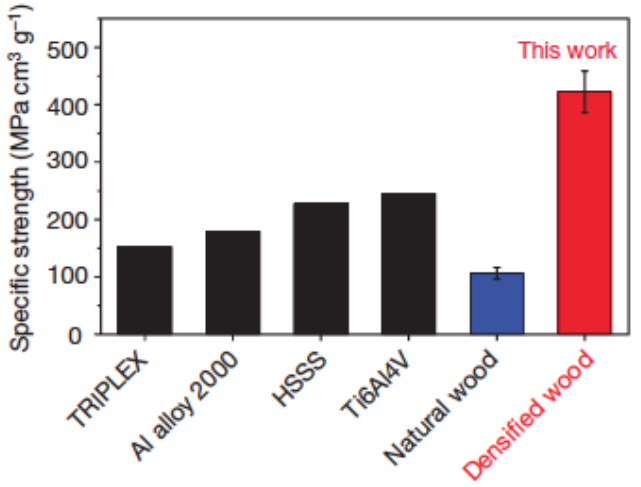


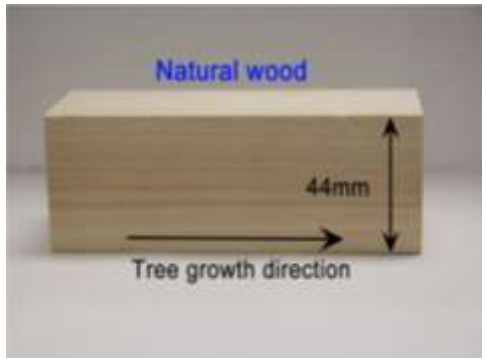
Nature, 2018, 554, 224-228

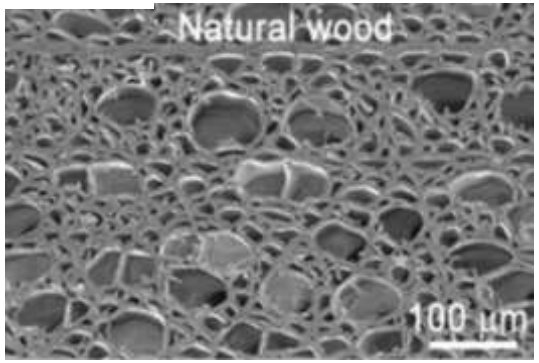
Superb Mechanical Properties of Densified Wood

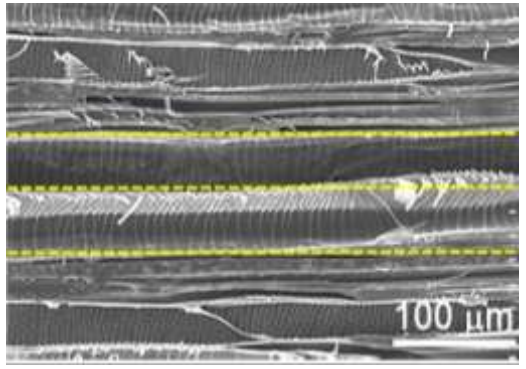


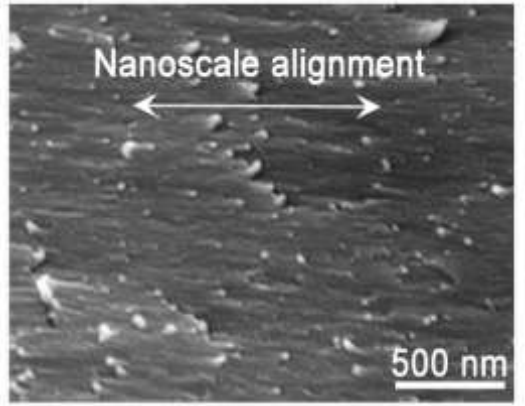




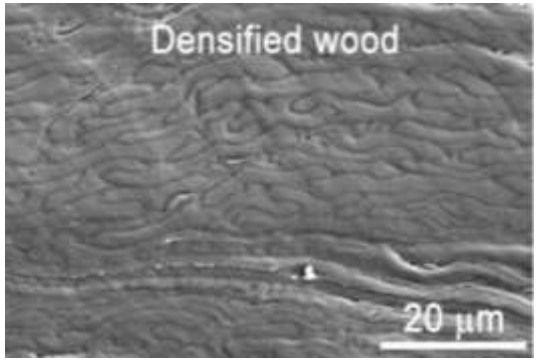


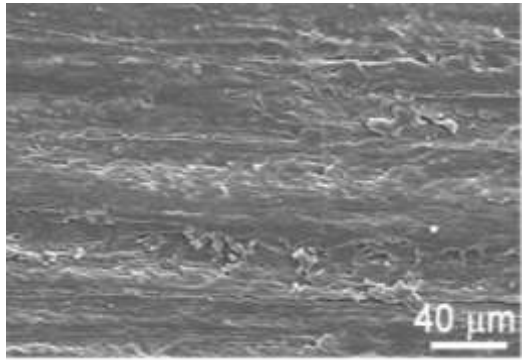


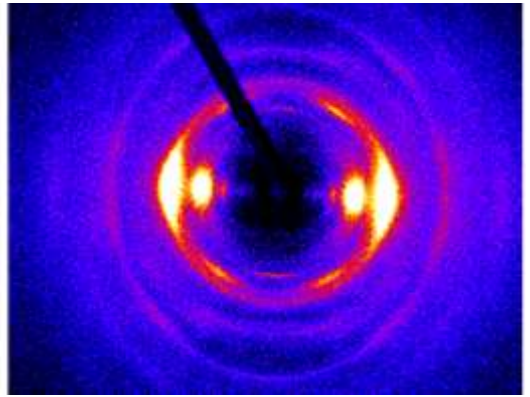








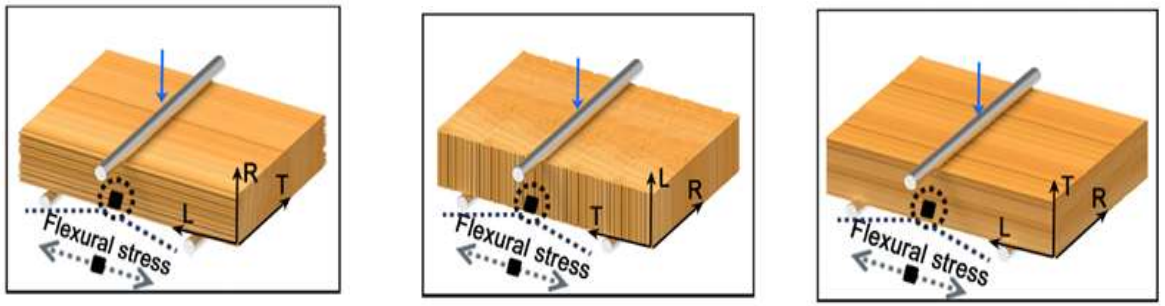


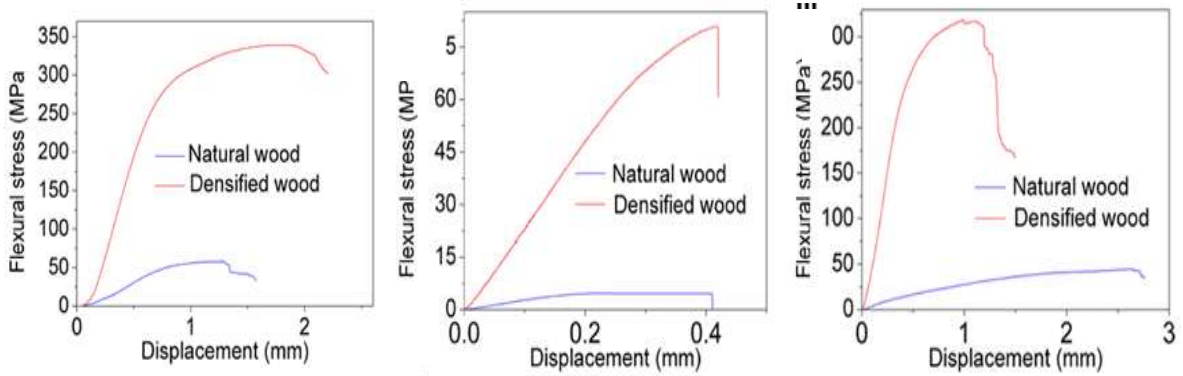


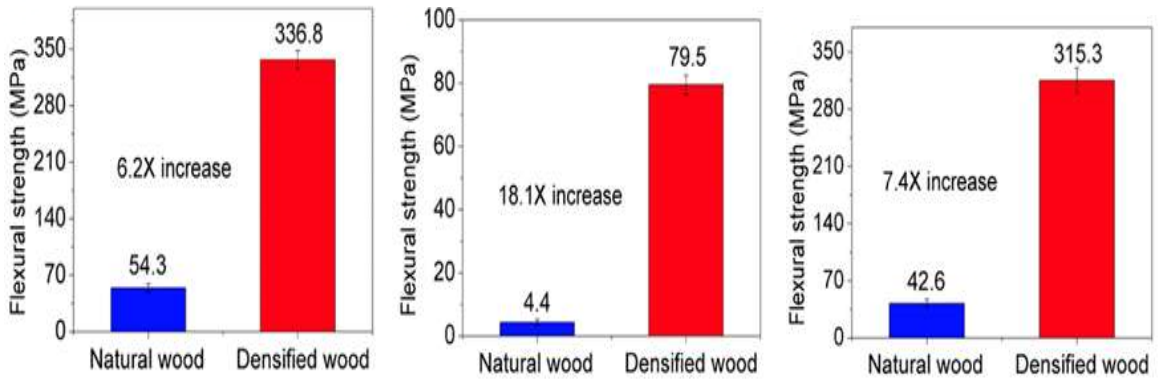
Nature, 2018, 554, 224-228

Superb Mechanical Properties of Densified Wood

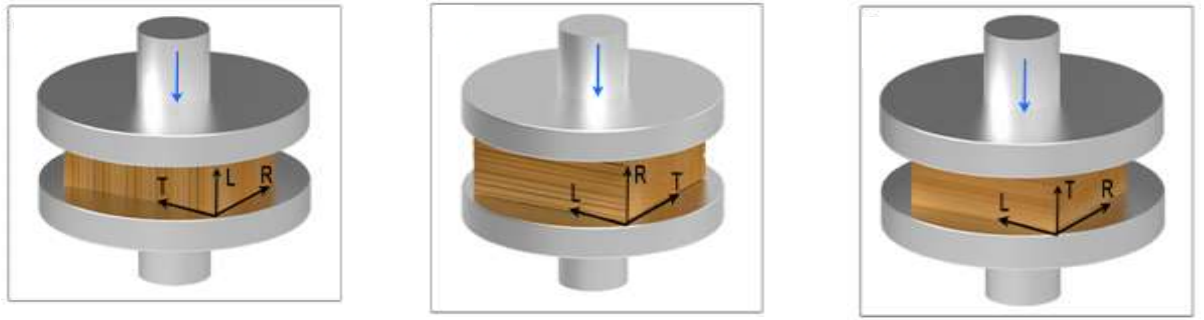
Bending

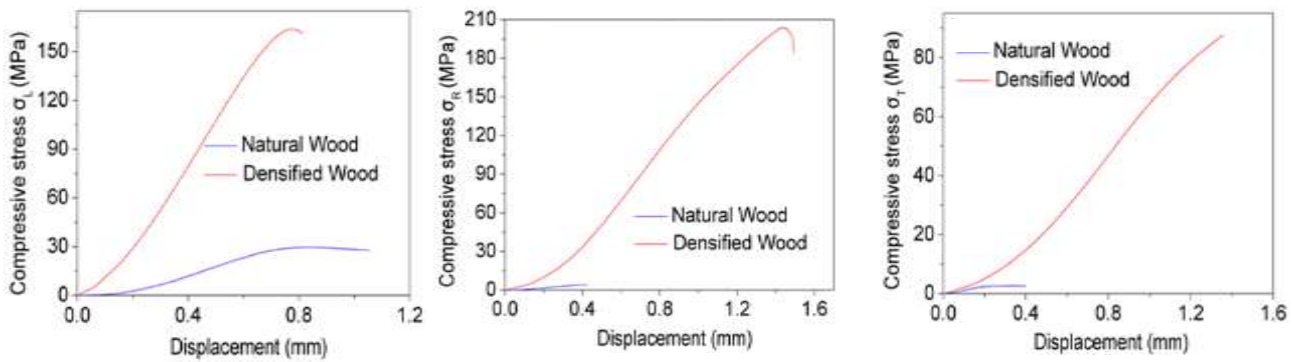


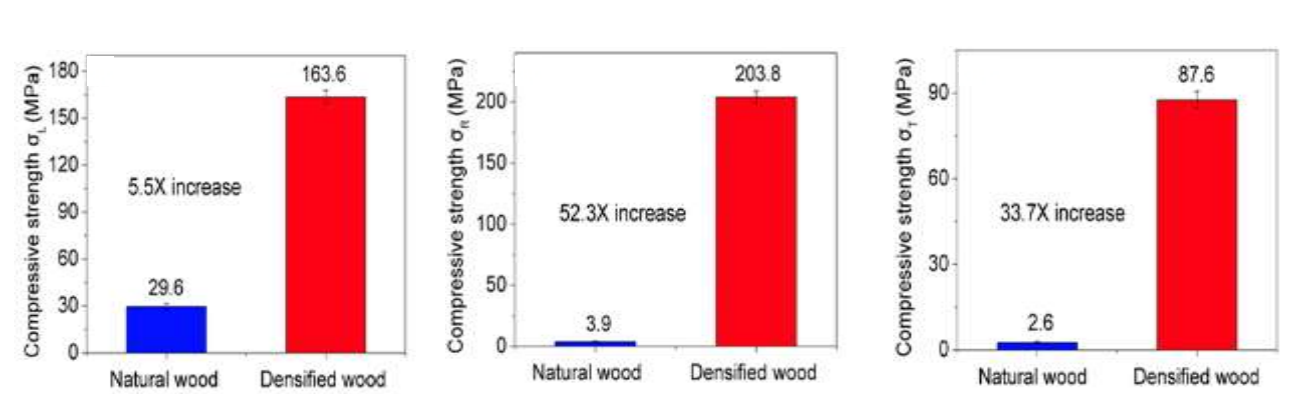




Compression



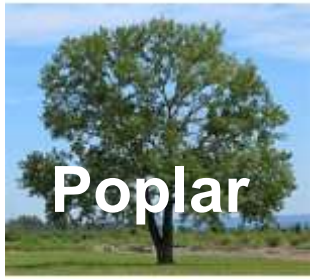




Nature, 2018, 554, 224-228

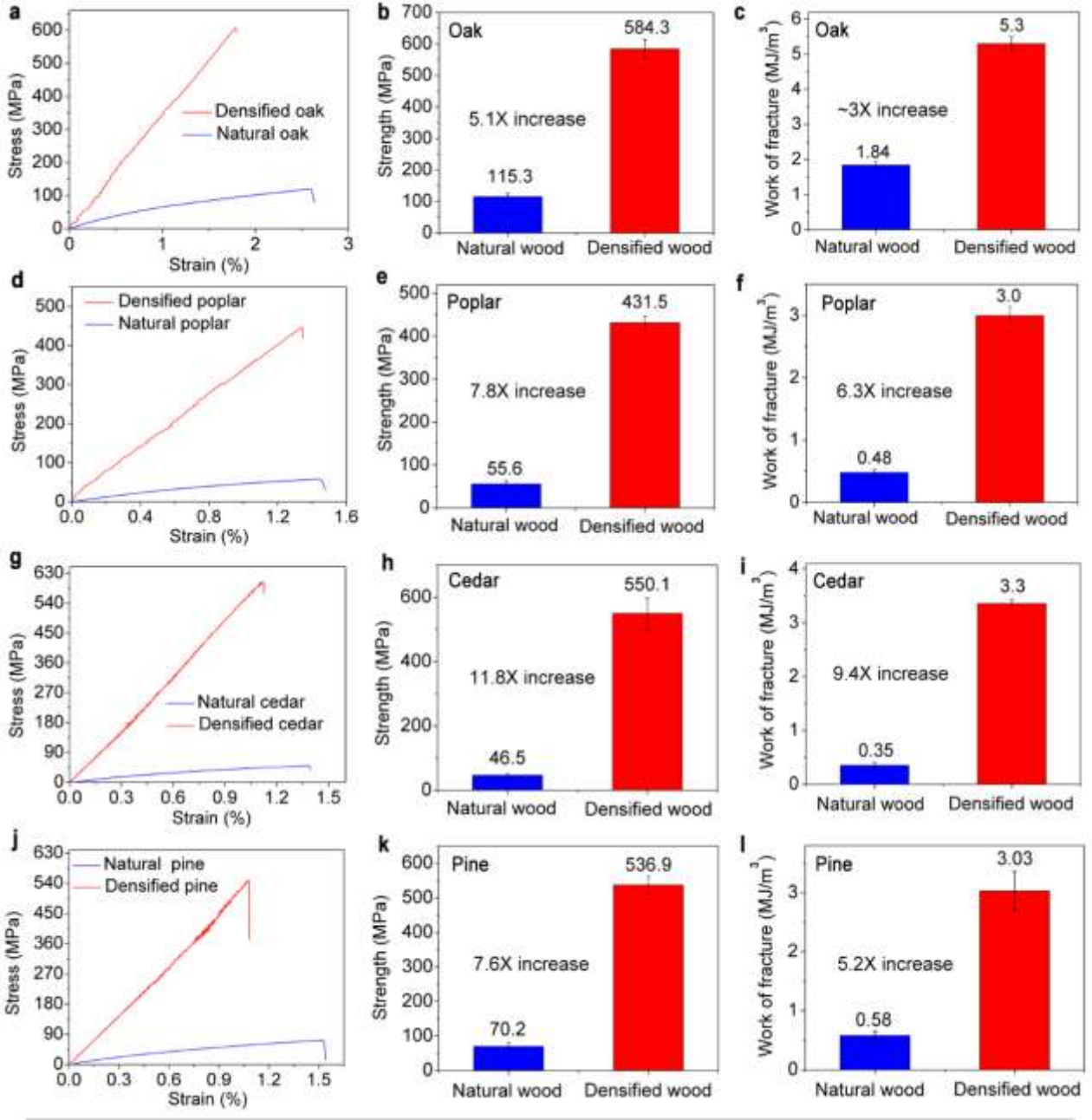
A Universal Process for Various Wood Species







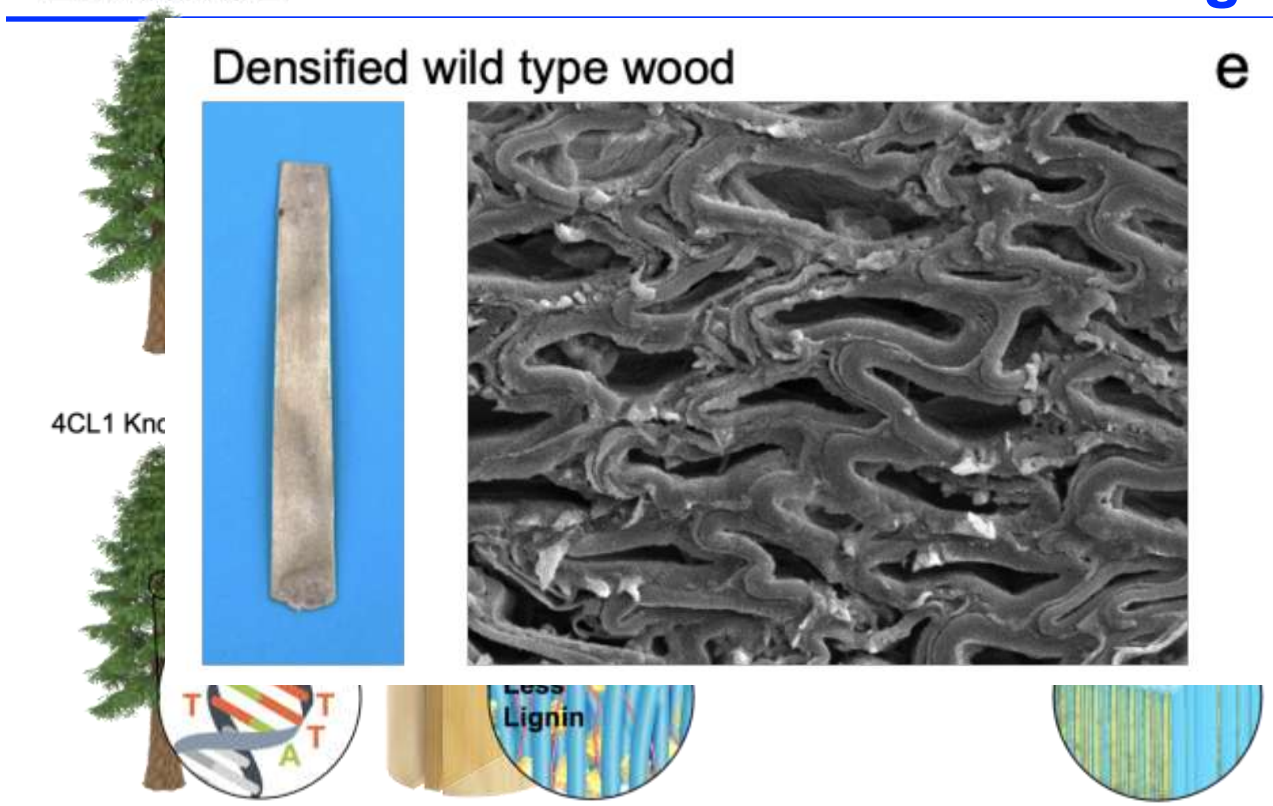


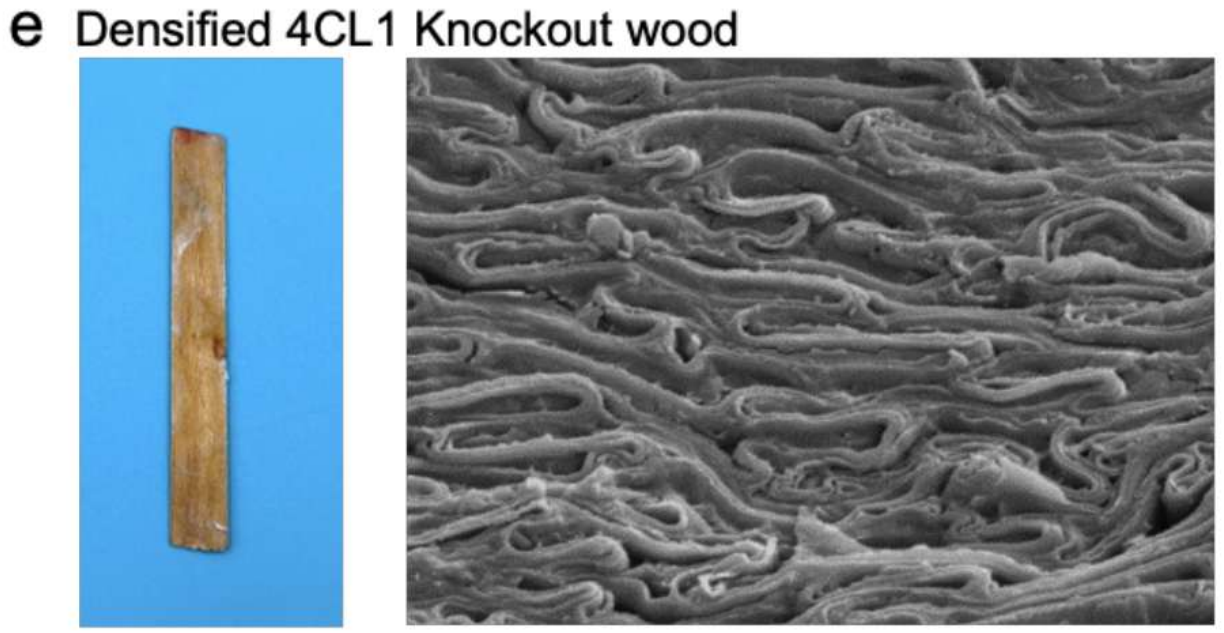


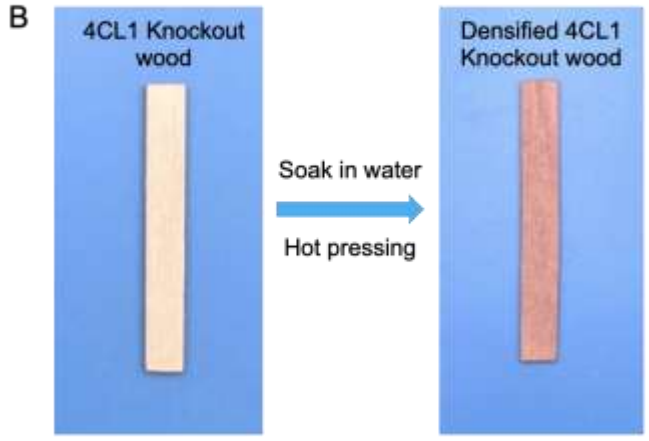


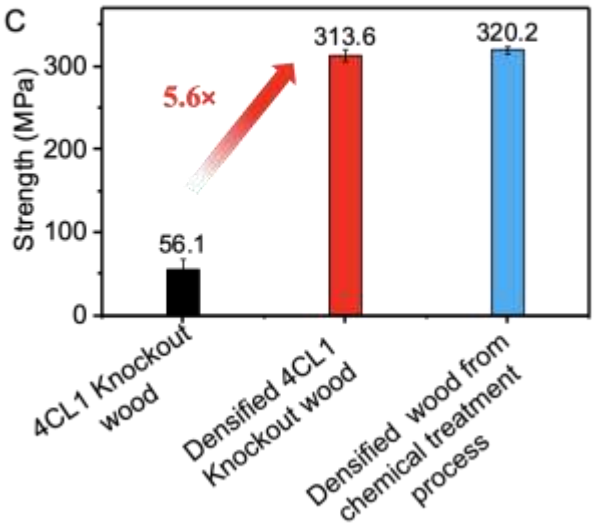
Nature, 2018, 554, 224-228

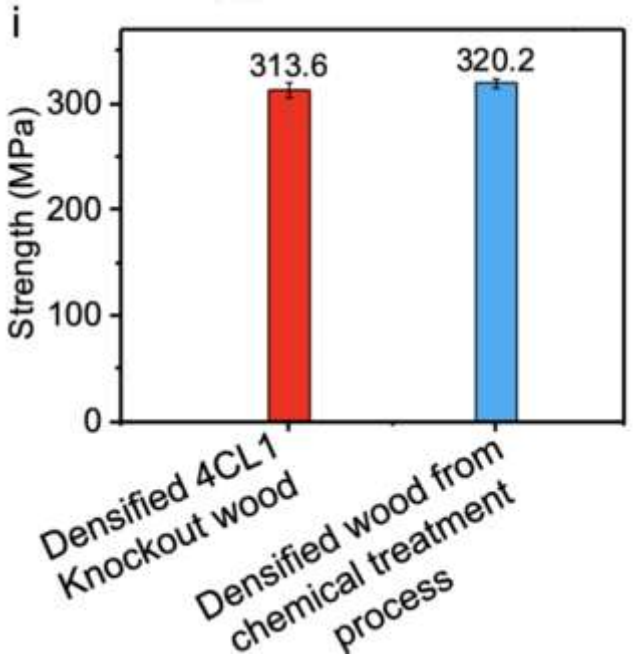
Genome-edited Trees for High-Performance Engineered











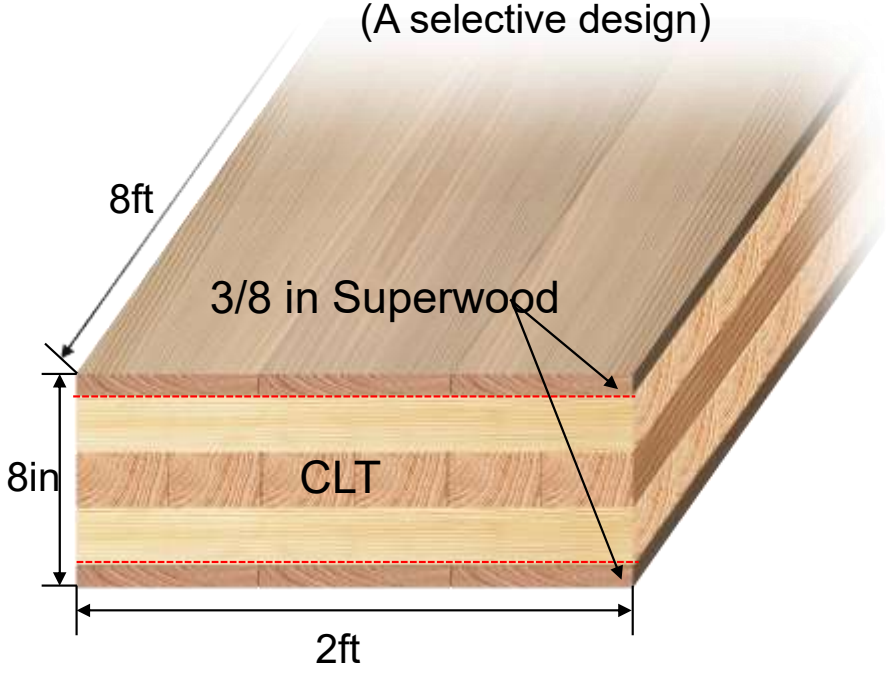


Prof. Yiping Qi

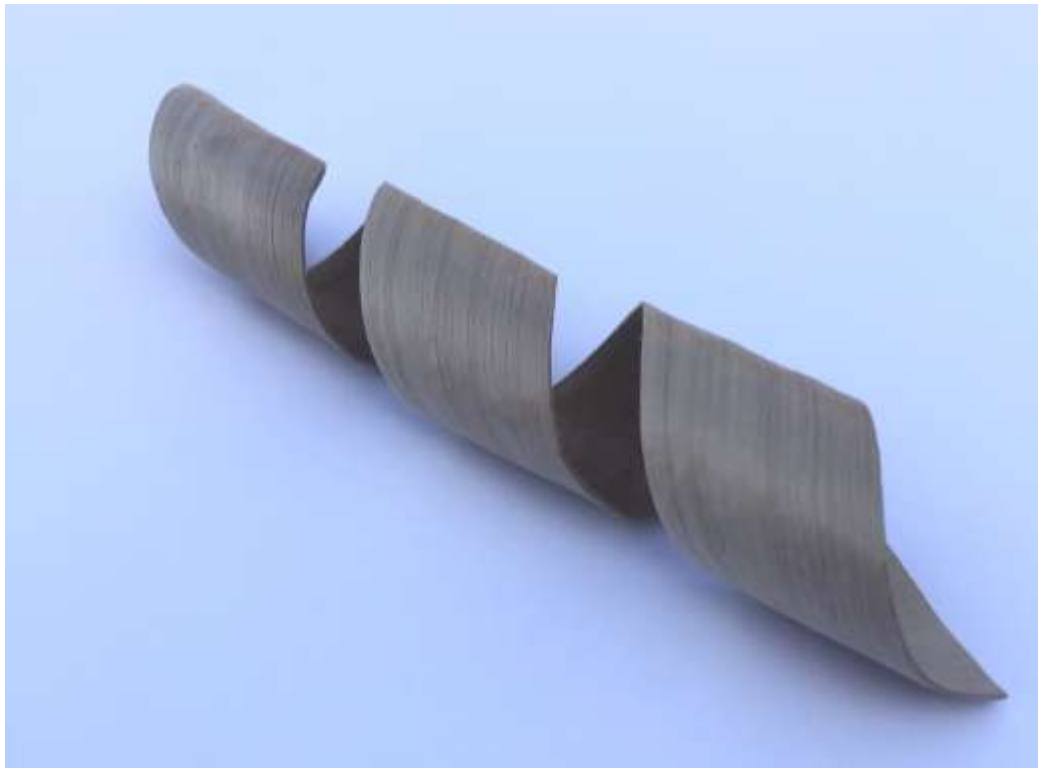
Materials Properties

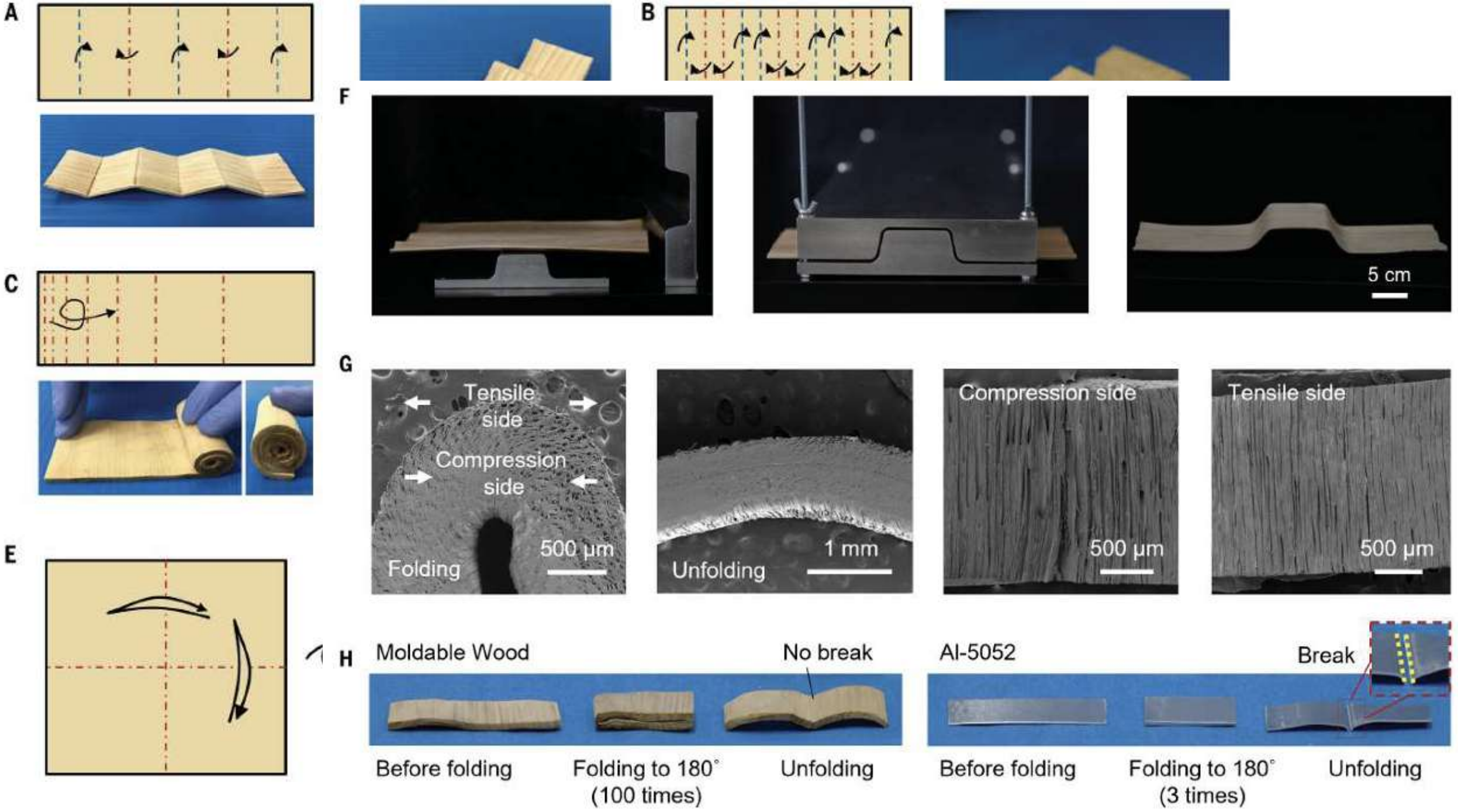
Superwood-reinforced CLT

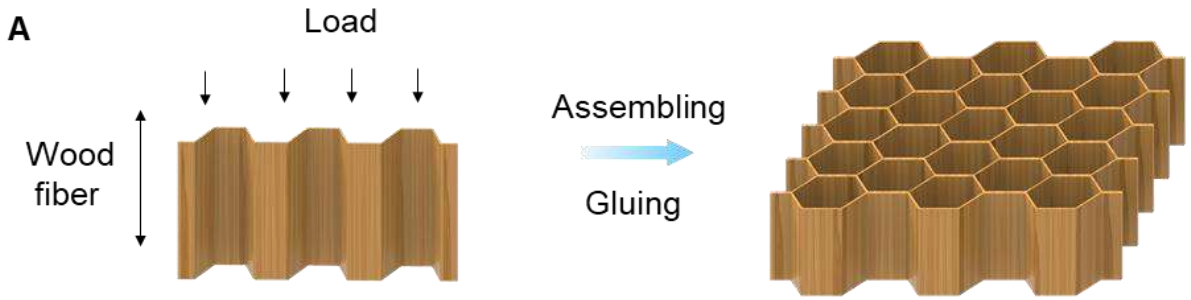
(A selective design)

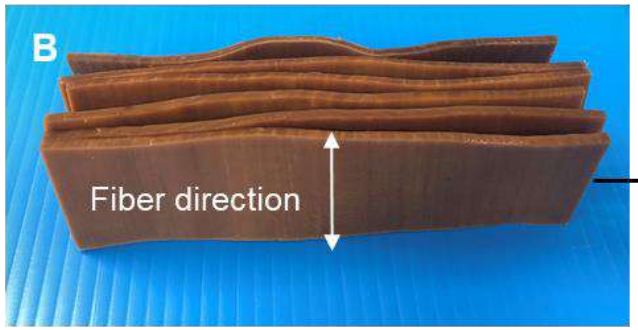


Shapes

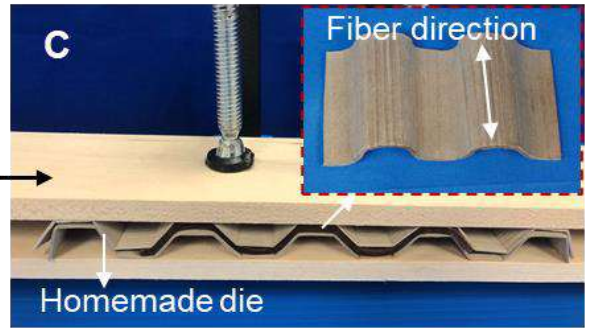



A
B
C
E
F
5 cm
G
Tensile side
Compression side
500 μm
Folding
1 mm
Unfolding
Compression side
500 μm
Tensile side
500 μm
H
Moldable Wood
No break
Before folding
Folding to 180°
(100 times)
Unfolding
Al-5052
Break
Before folding
Folding to 180°
(3 times)
Unfolding

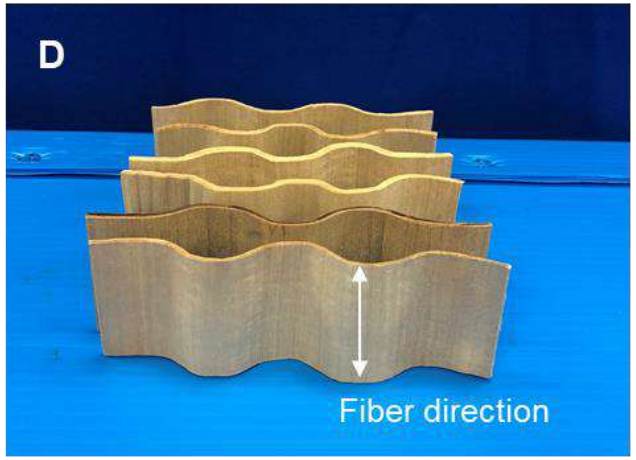




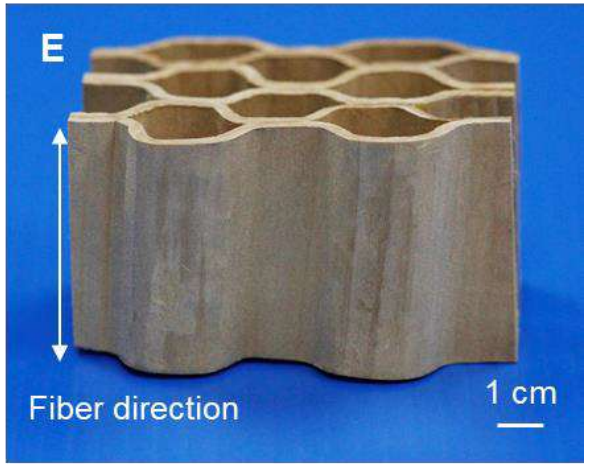
Moldable Wood



Mold



3D-Molded Wood corrugated structure



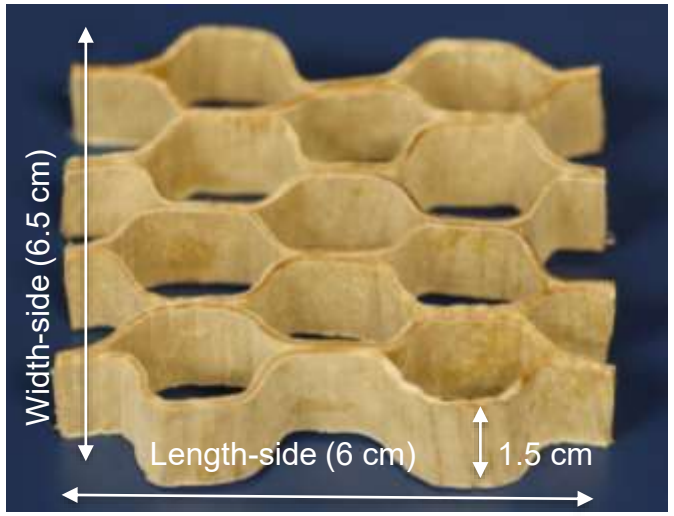
3D-Molded Wood honeycomb core





The 3D-Molded Wood for Strong, Lightweight Honeycomb

3D-Molded Wood honeycomb core

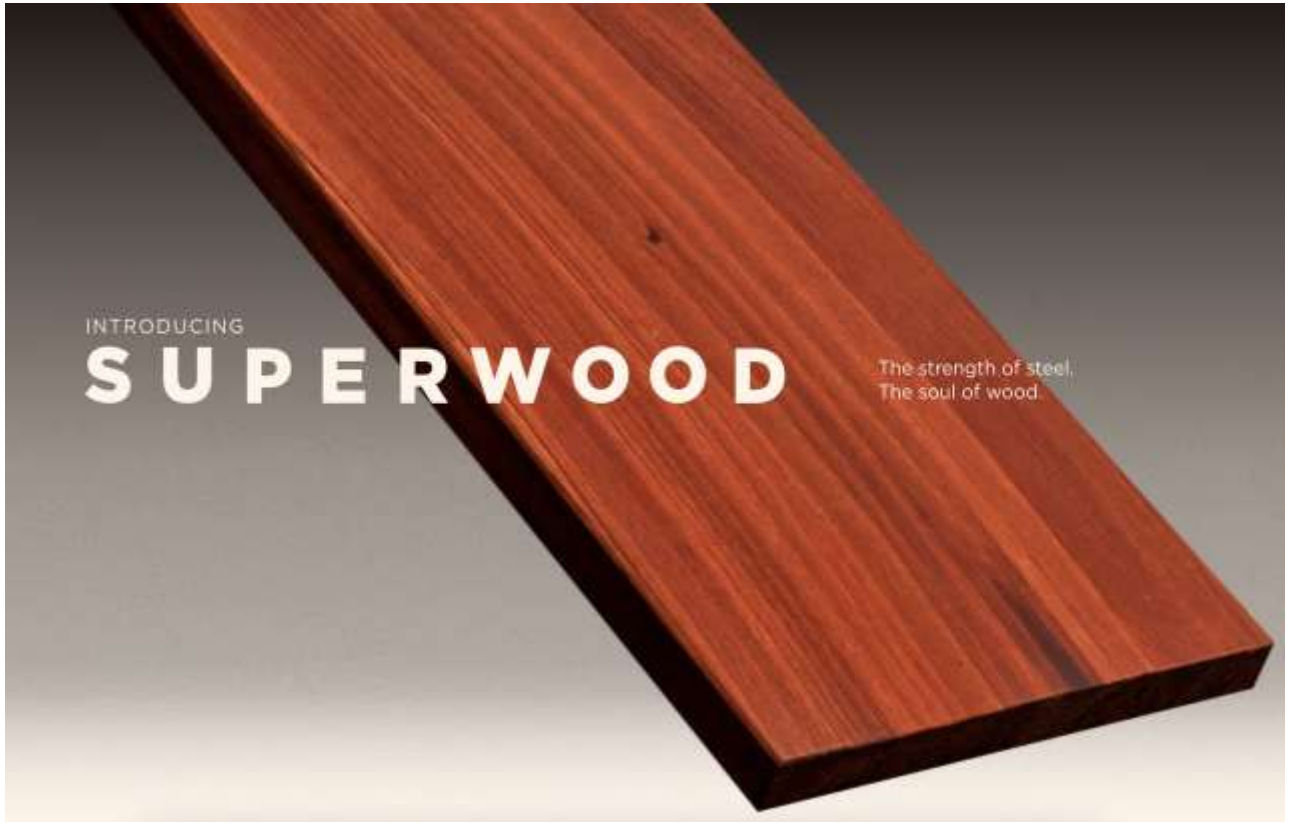








SuperWood



- Stronger than steel but 6-times lighter
- ~ 100% wood and produces zero waste
- Applicable to any kind of wood
- Fire and termite resistance
- It is gorgeous!

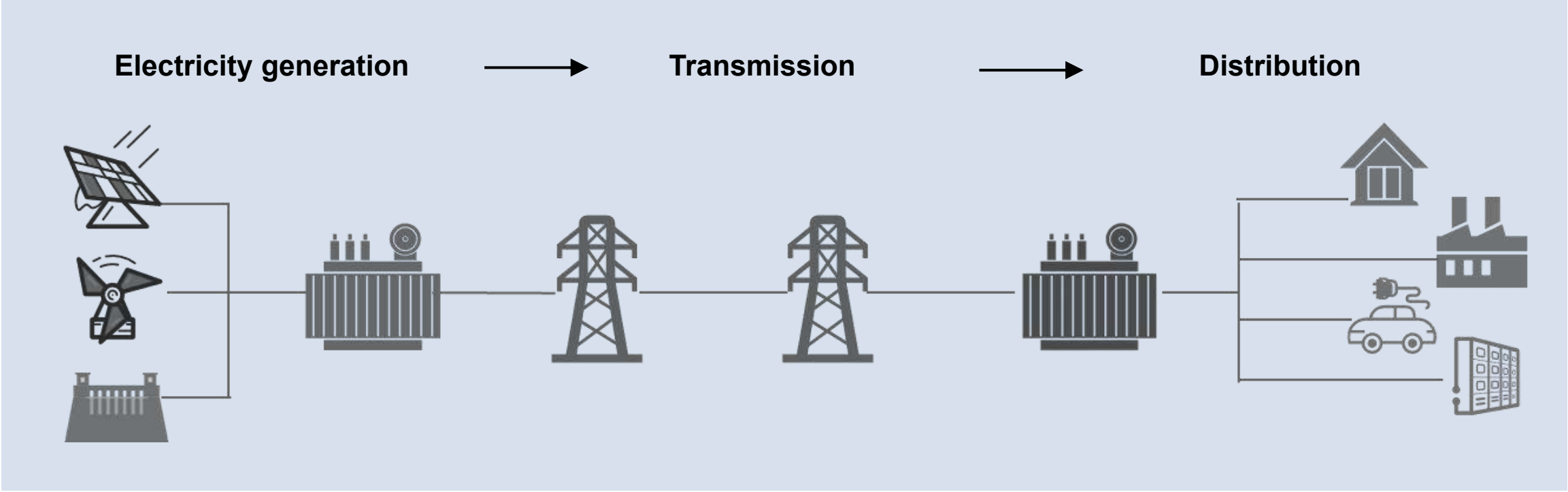
Applications of SuperWood

ChatGPT

Rank	Application	Potential products and advantages
1	Structural building materials	Beams, columns, load-bearing panels, and structural framing; potentially replacing steel and conventional engineered lumber
2	Automotive components	Vehicle floors, door panels, roof structures, battery enclosures, and crash-energy-absorbing components
3	Furniture	Tables, chairs, cabinets, shelving, and premium furniture with thin, high-strength designs
4	Flooring and decking	High-durability flooring, stair treads, outdoor decking, and wear-resistant surfaces
5	Building facades and cladding	Exterior panels, architectural facades, and lightweight building envelopes
6	Doors and windows	High-strength doors, door frames, window frames, and security-resistant panels
7	Aerospace and drones	Lightweight interior panels, UAV structures, and selected noncritical aircraft components
8	Battery pack structures	Battery enclosures, structural supports, module separators, and impact-resistant battery packaging
9	Transportation infrastructure	Railway interiors, shipping container panels, truck trailers, and transit vehicle components
10	Protective and security materials	Impact-resistant panels, protective barriers, security doors, and multilayer protective structures

SuperWood Transformer for Electric Grid

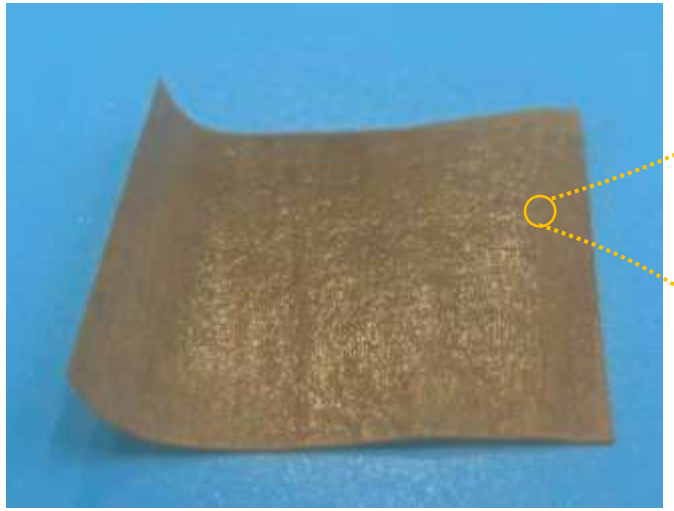
- **Growing energy demands and renewable energy integration are have created the urgent need to build better electric grid infrastructure with high performance, enhanced reliability, and longer lifetime.**



Electricity generation and distribution: growing and fluctuated demand

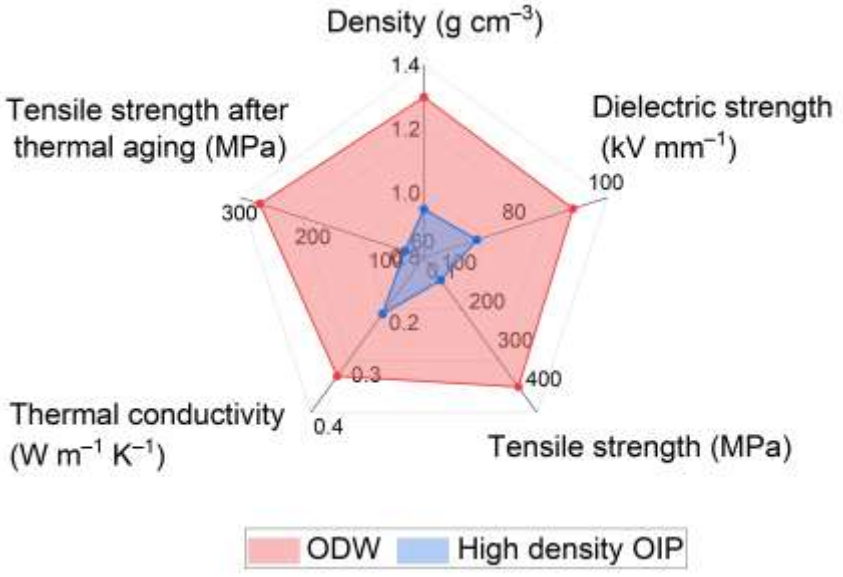
Oil-impregnated SuperWood

- **Starting from wood veneer, a new paper insulation structure based on oil-impregnated densified wood veneer (ODW) is proposed.**





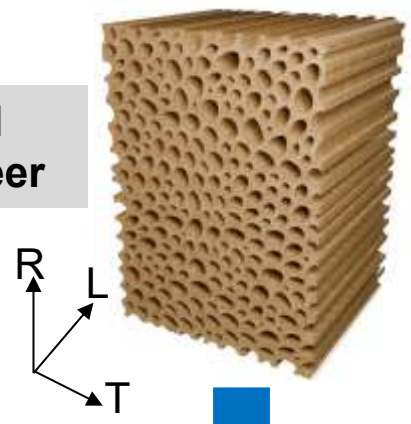
- Nanoscale Oil in the pores of densified wood
- High dielectric strength
- High through-thickness thermal conductivity

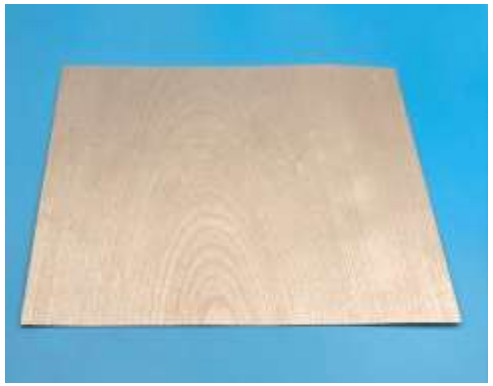


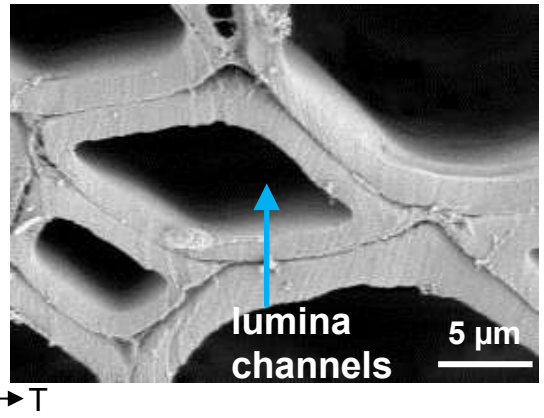
Morphology and Performance of Super Wood Transformer

- Delignified wood veneer shows a loosened structure with enlarged lumina channels from 1 to 50 μm
- After oil impregnation and mechanical pressing, the ODW is formed with densely packed laminated structure, potentially confining any remaining adsorbed oil into the collapsed lumina space and pores within the cellulose fibers.

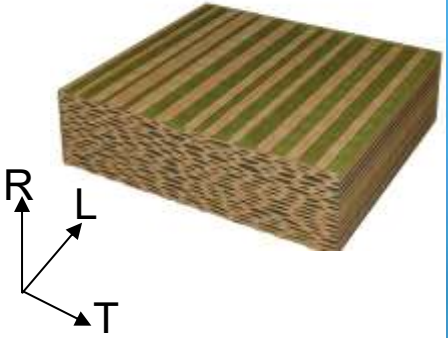
Delignified wood veneer

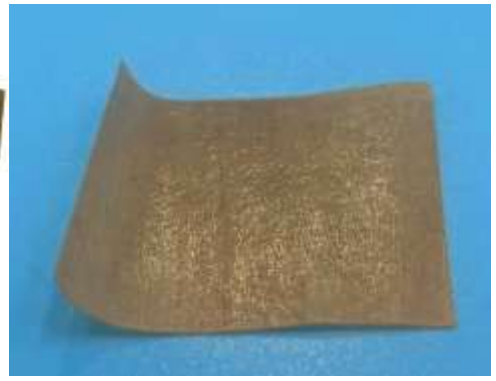


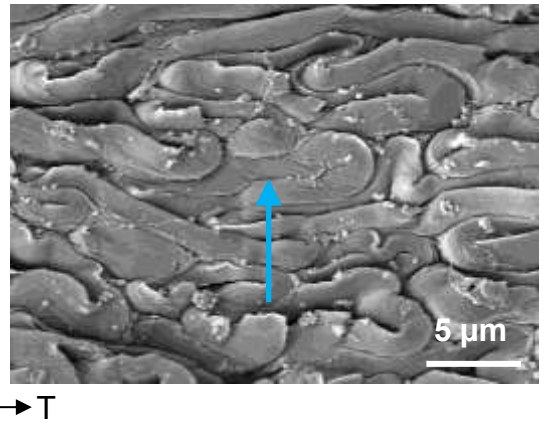


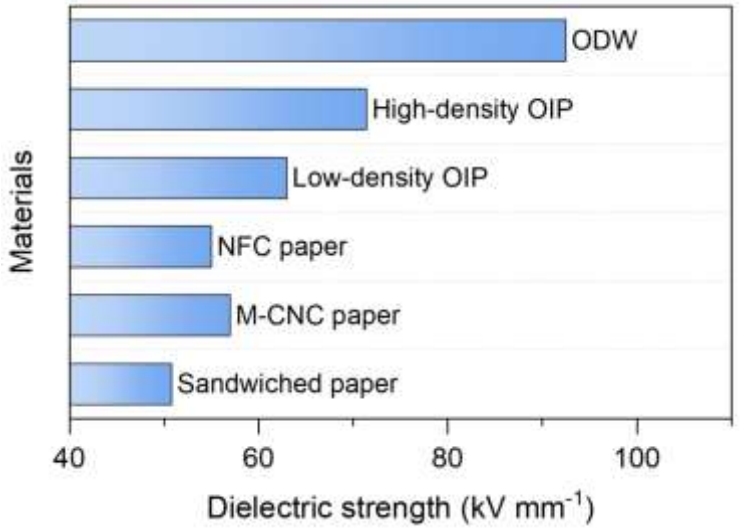


ODW









- ODW shows a record high dielectric strength of 105 kV mm^{-1}.



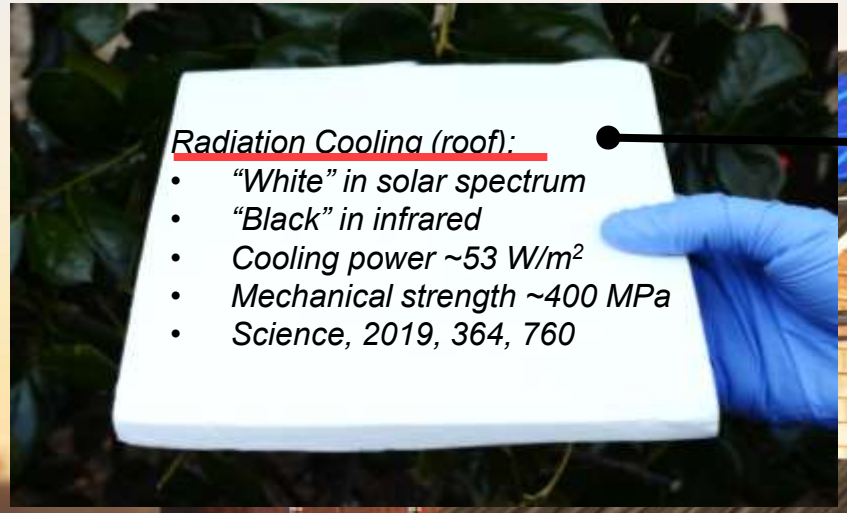
Jonathan Scott of Property Brothers

Technology 3:

Optically and Thermally Engineered Wood

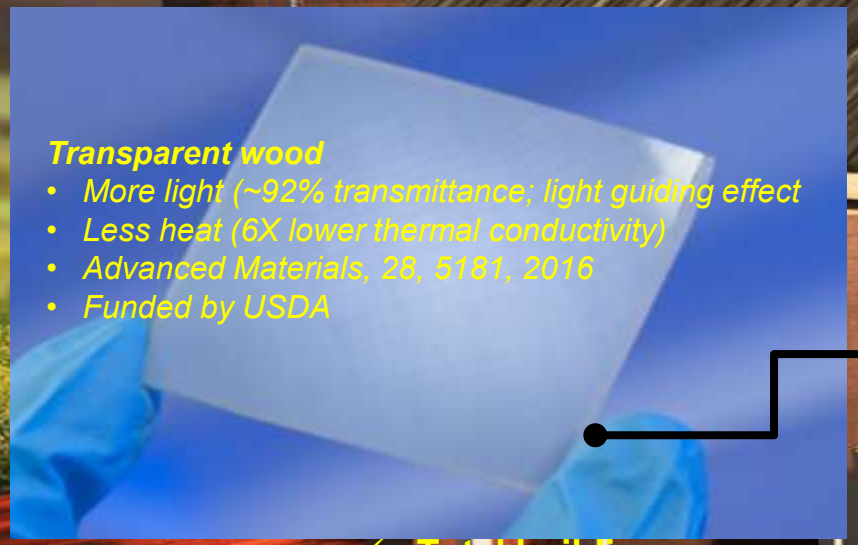
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Building Energy Efficiency and Materials Challenges



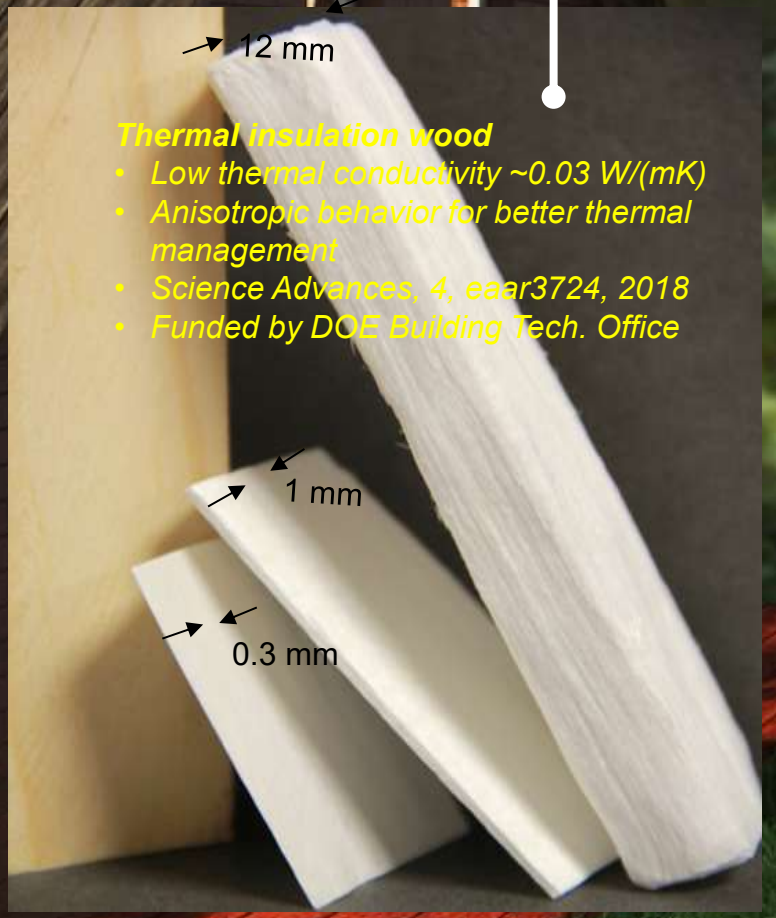
Radiation Cooling (roof):

- *"White" in solar spectrum*
- *"Black" in infrared*
- *Cooling power ~53 W/m^2*
- *Mechanical strength ~400 MPa*
- *Science, 2019, 364, 760*



Transparent wood

- *More light (~92% transmittance; light guiding effect*
- *Less heat (6X lower thermal conductivity)*
- *Advanced Materials, 28, 5181, 2016*
- *Funded by USDA*



Thermal insulation wood

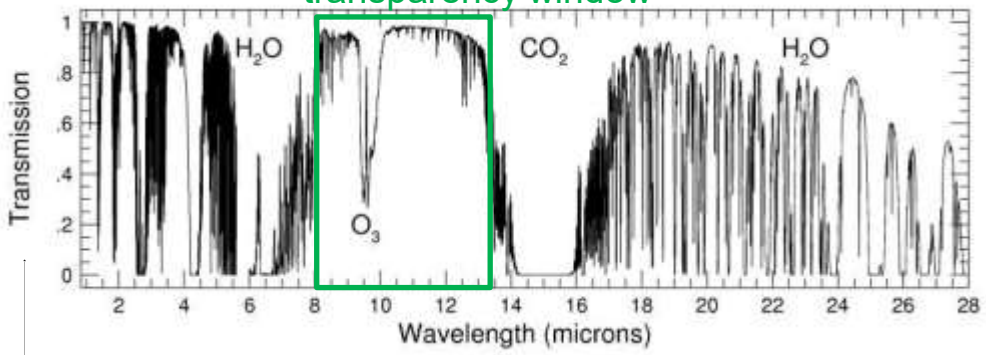
- *Low thermal conductivity ~0.03 W/(mK)*
- *Anisotropic behavior for better thermal management*
- *Science Advances, 4, eaar3724, 2018*
- *Funded by DOE Building Tech. Office*

- ✓ **Total building energy consumption ~$220 billion/year (~40% total energy)**
- ✓ **Heating/cooling ~50-70% of energy used in the average American home**
- ✓ **~ 30% leaks through windows (glass)**
- ✓ **~ 25% energy leaks through walls**

Spectrum Engineering: Universe, Sun, Clouds, and Buildings

Universe ~3 K

8-13 μm
transparency window



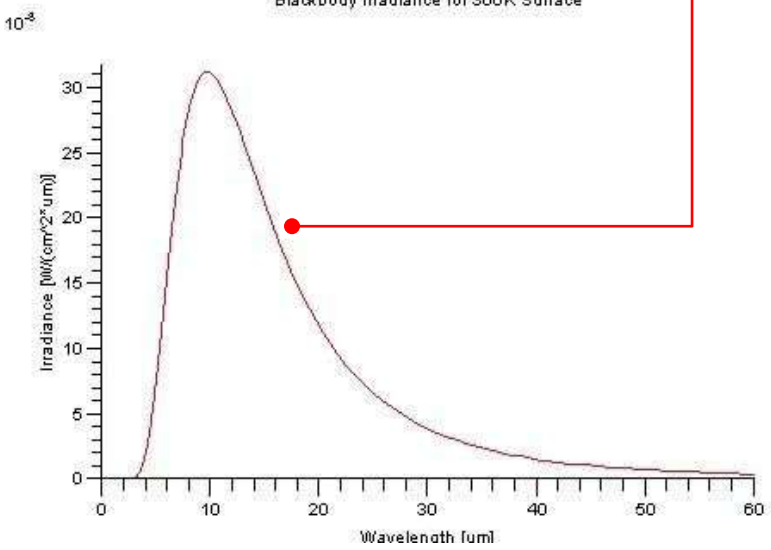
Sun ~5778 K

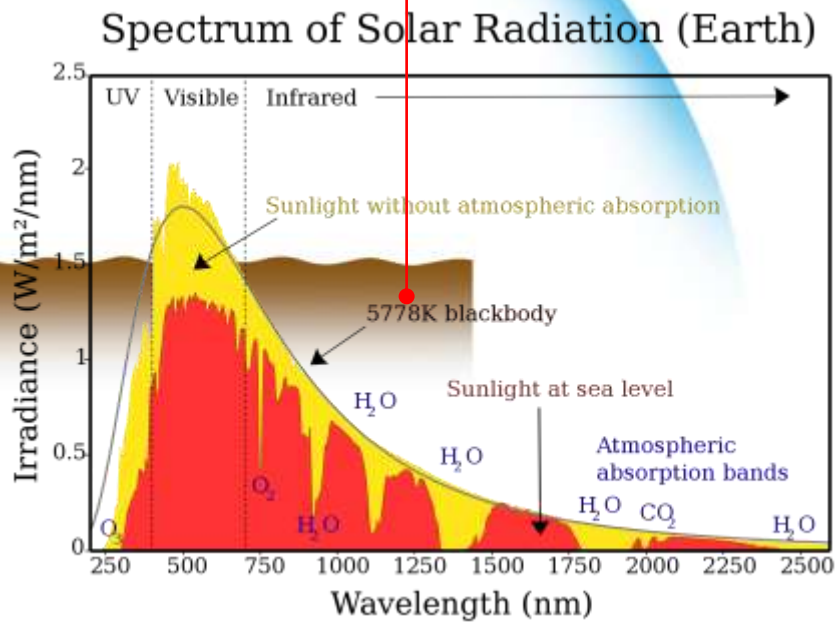
Mid-IR cooling

Solar heating
~ 1000 W/m^2

Roof ~ 300 K

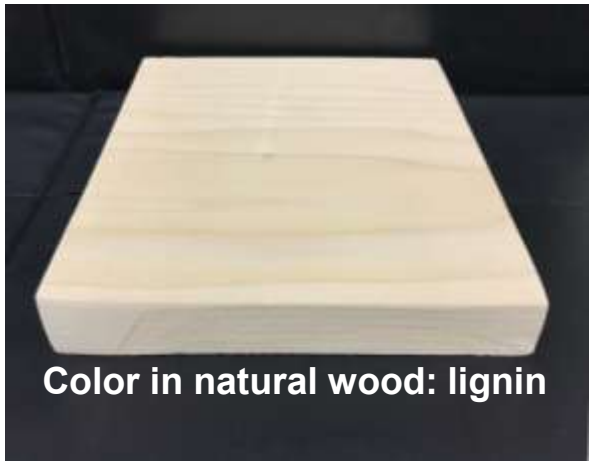
building

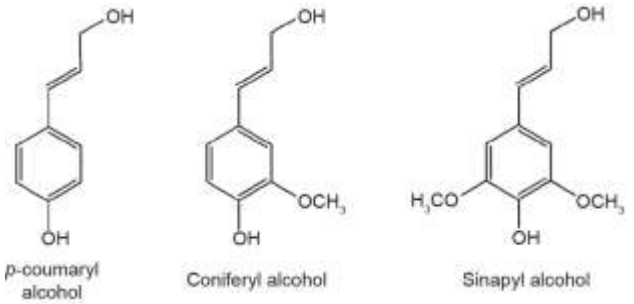


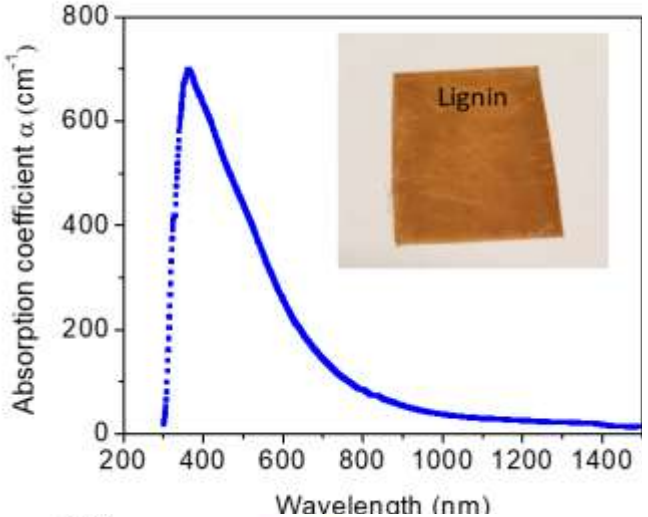


Cooling in mid-IR > Heating in solar spectrum

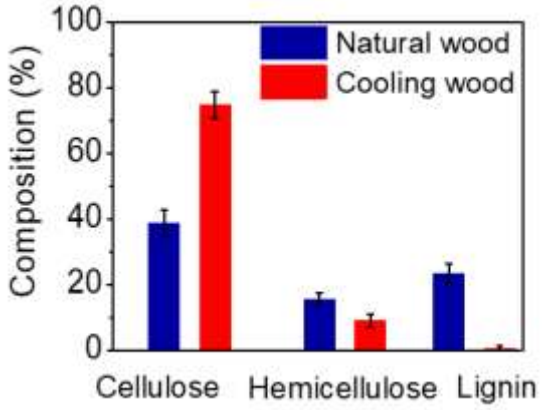
Completely Delignified Wood (White in Solar Spectrum)



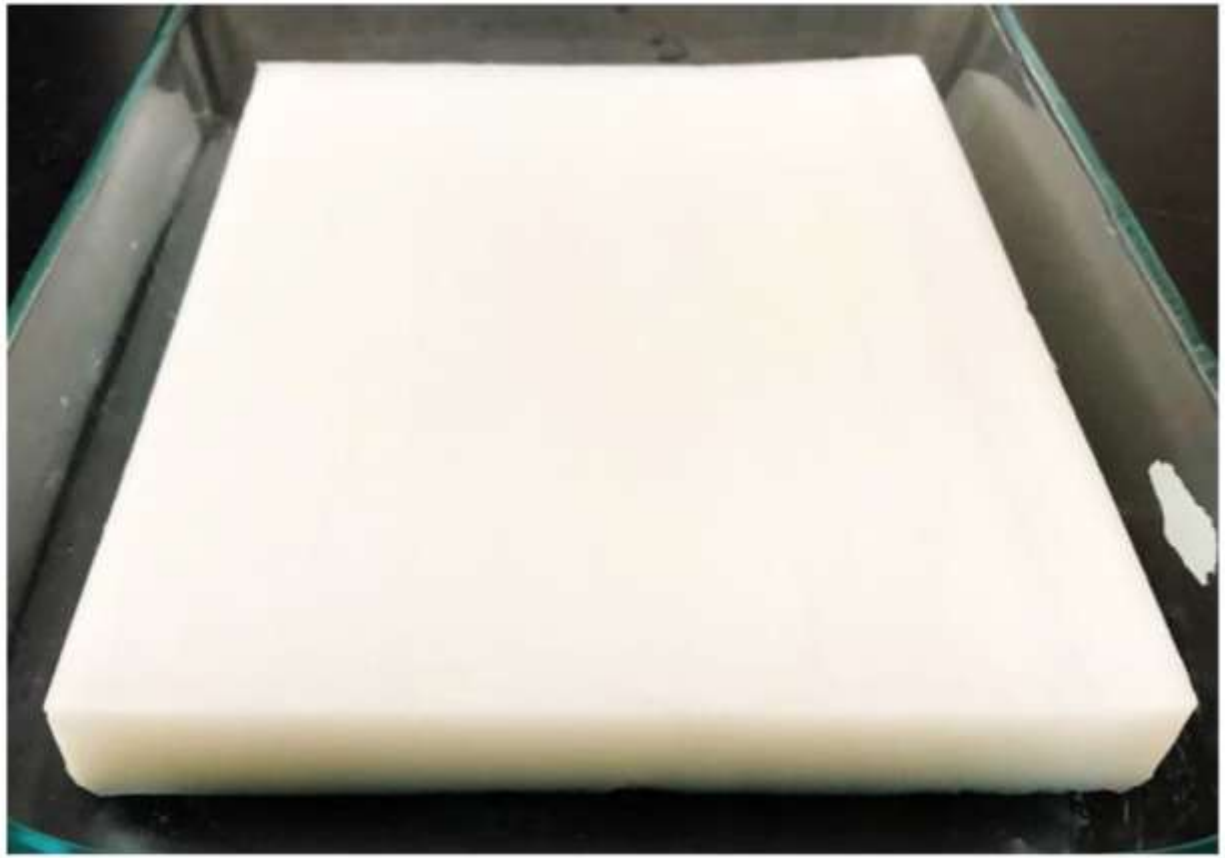








We invented a process to <u>completely</u> remove lignin without destroying the fiber alignment in wood.

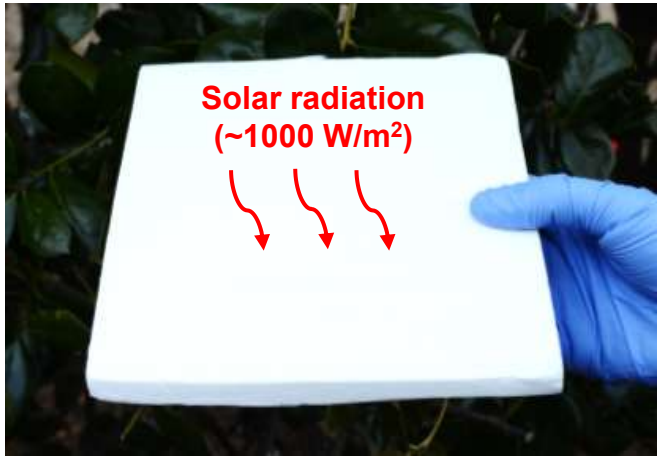


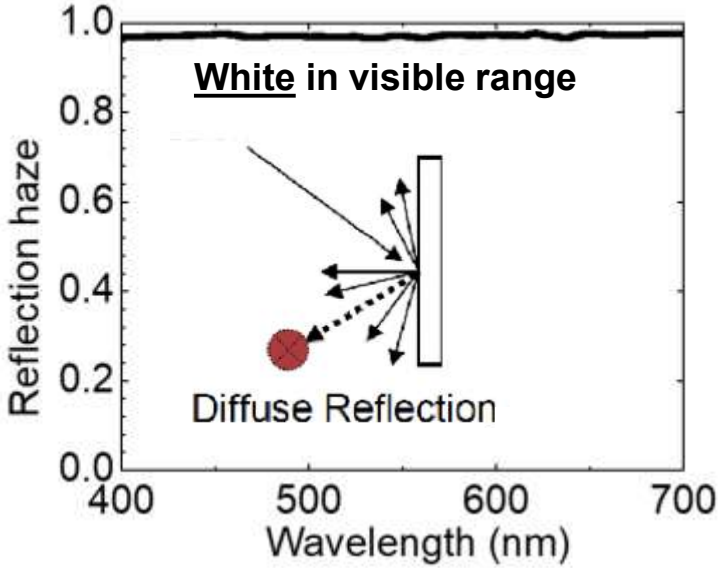
- Preserve the alignment.
- Scalable (demonstrated ~1 inch in thickness).
- Diffusion is the limiting factor.

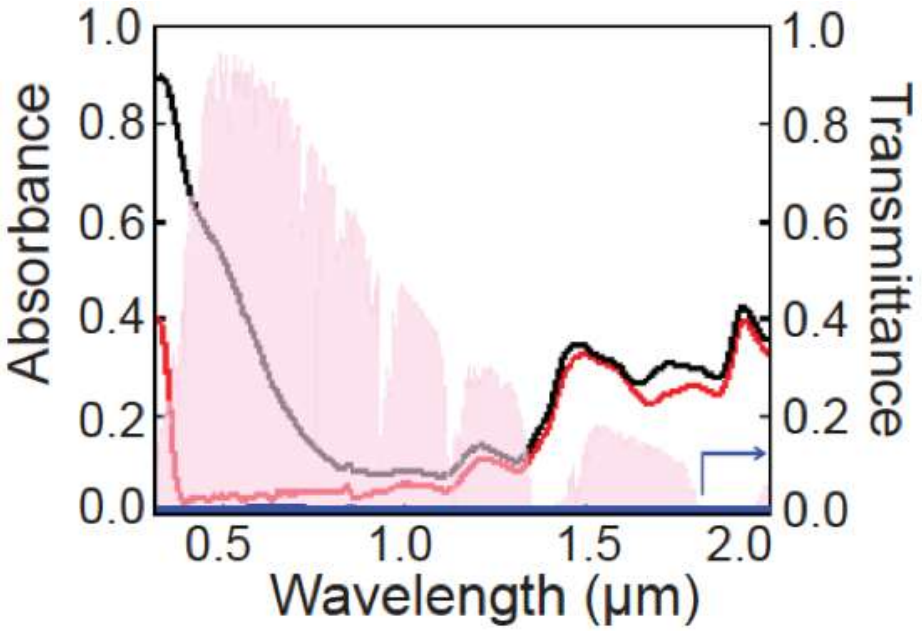
Science, 2019, 364, 760

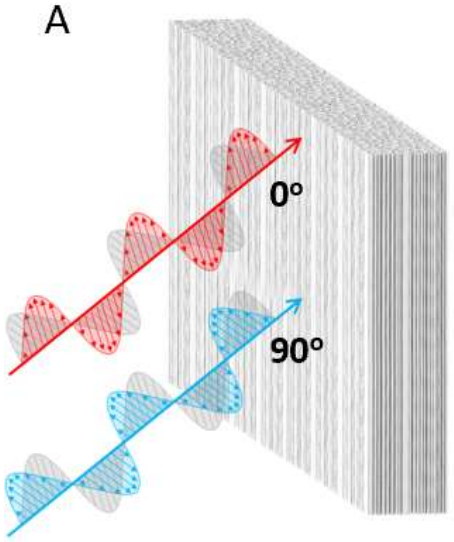
International Application No.: PCT/US2018/051091, Priority Data: 62/559,147 15.09.2017

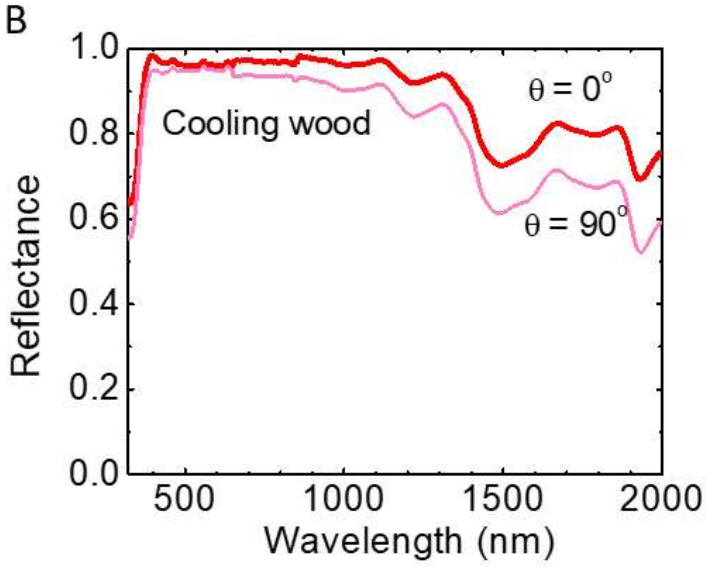
Cooling Wood in Solar Spectrum: Integrated Heating Power







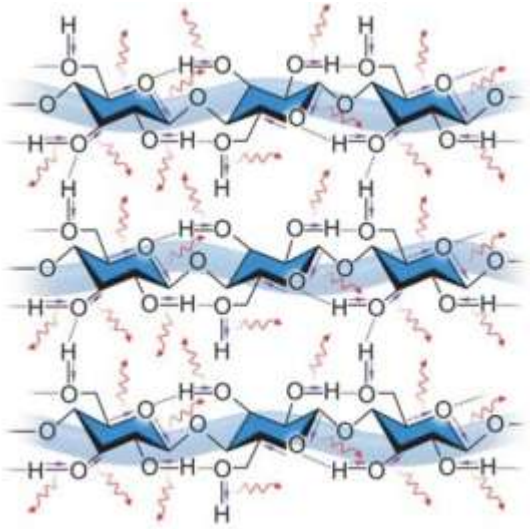




- Energy density of solar radiation ~1000 W/m^2 at the Earth's surface
- Highly reflective (~96%) in visible region (majority of solar energy)
- Absorption happens mainly in the near infrared of solar spectrum (weak solar radiation)
- Integrated solar adsorption P_{solar} ~ 53 W/m^2.

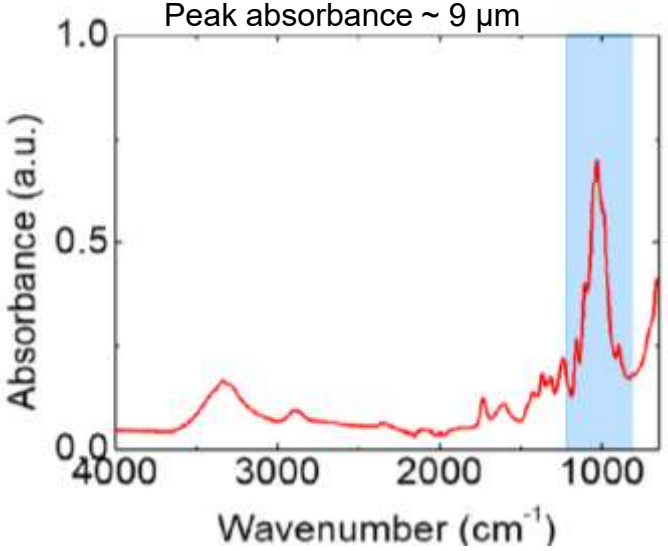
Science, 2019, 364, 760

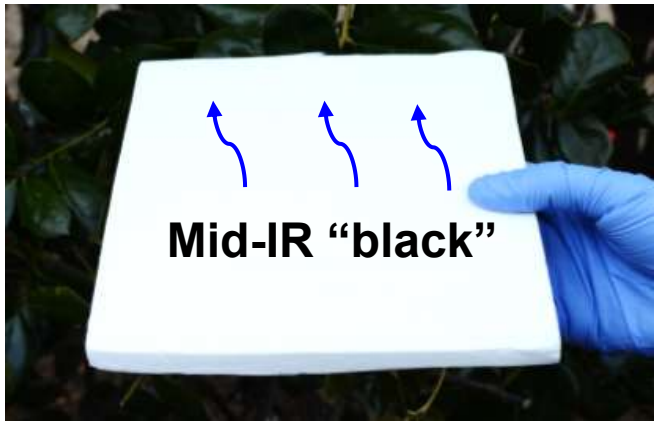
Mid-Infrared Spectrum: High Emissivity (Black)

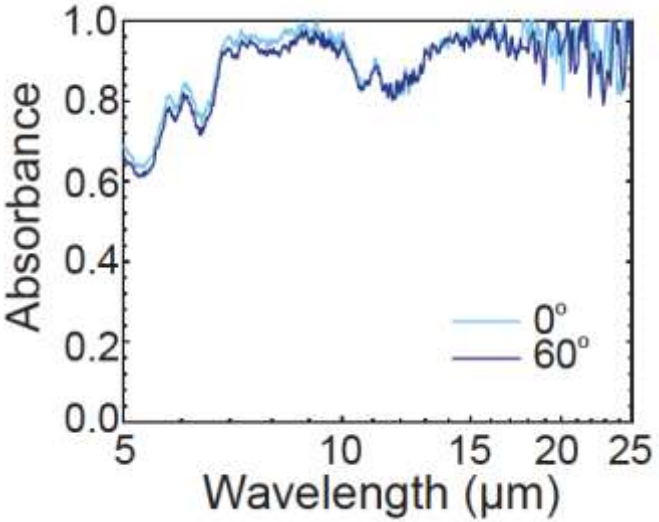


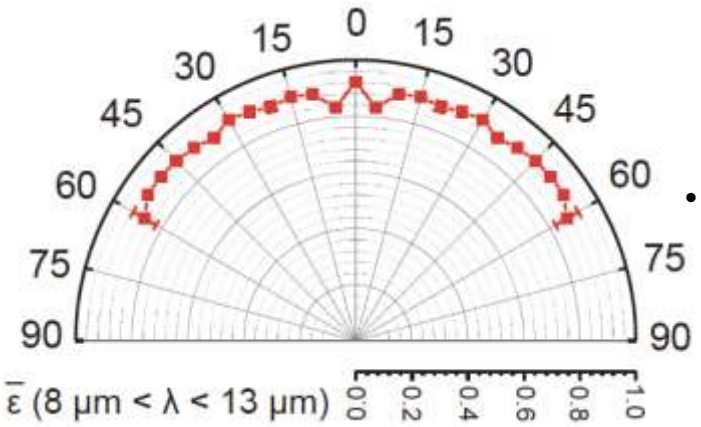
8 μm to 13 μm = 770 cm^{-1} to 1250 cm^{-1}

Peak absorbance ~ 9 μm









- **Total outgoing radiative cooling power density:**

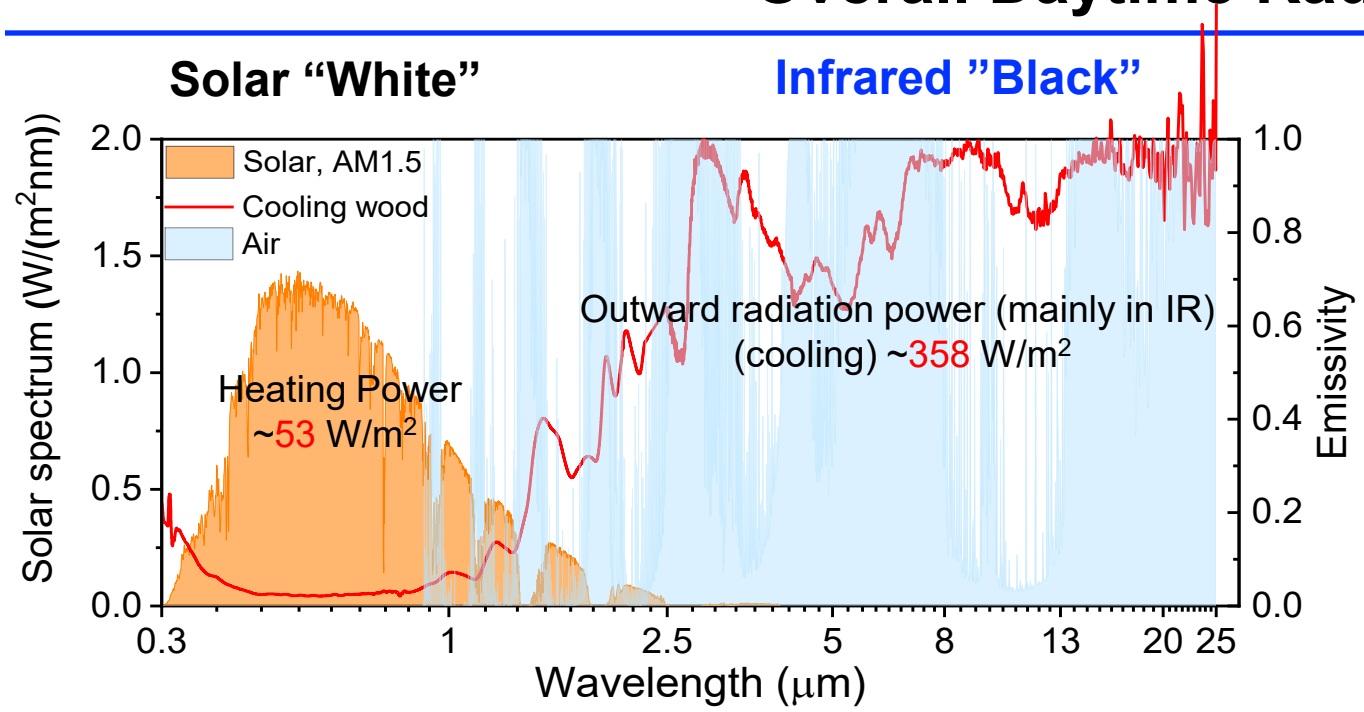
- $P_{rad}(T)$ is the emitted heat of the surface (mainly at mid-infrared)

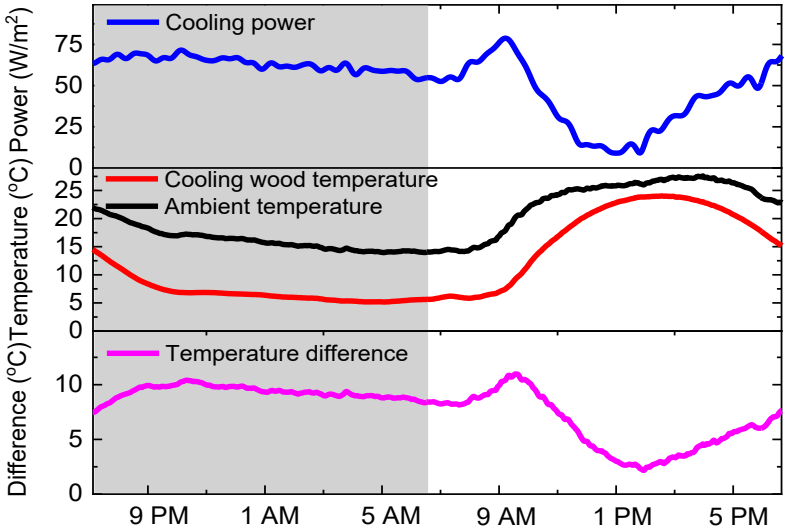
$$P_{rad}(T) = 2\pi \int_0^{\pi/2} sin\theta cos\theta d\theta \int_{0.3\ \mu m}^{25\ \mu m} \epsilon(\lambda) I_{b\lambda}(T) d\lambda = 358\ W$$

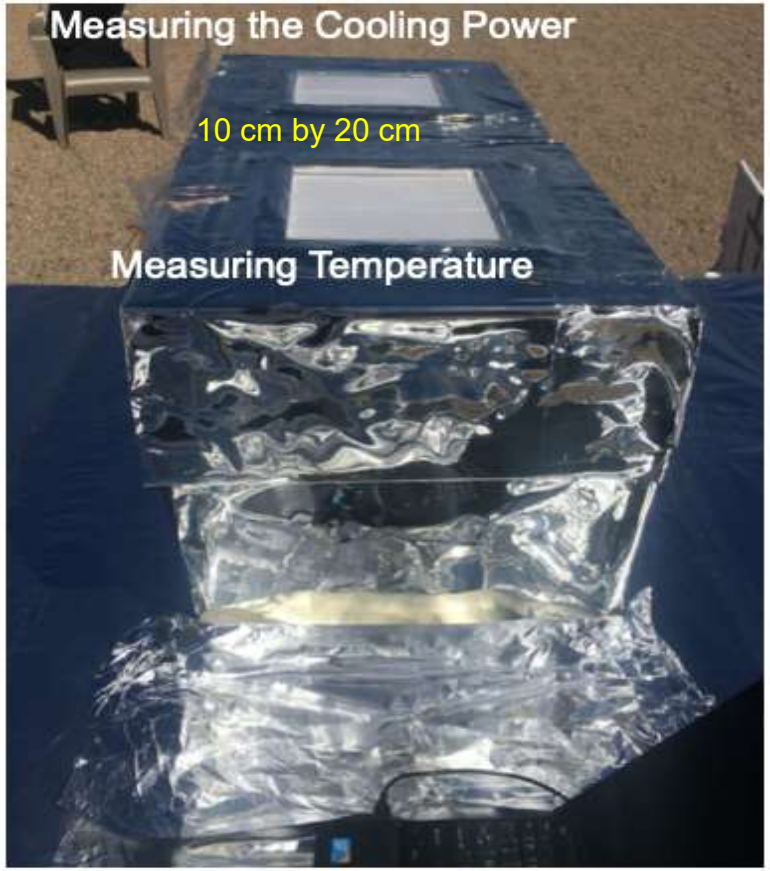
- Mid-Infrared wavelengths: 5-25 μm = Temperature 140-740 K.
- Building temperature ~ 300 K.
- High absorptivity α = High emissivity ε .

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Overall Daytime Radiative Cooling

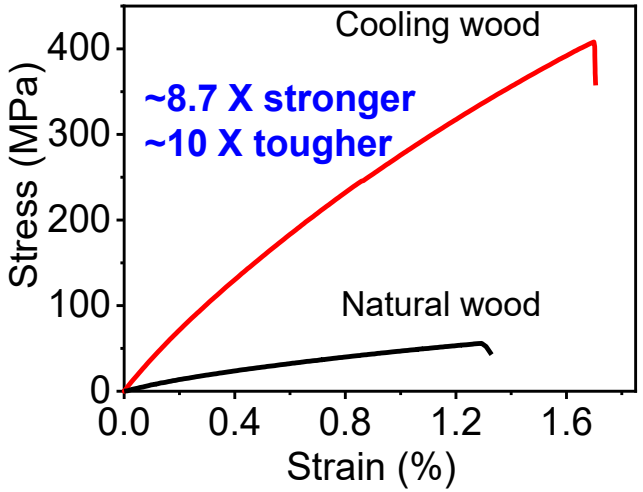


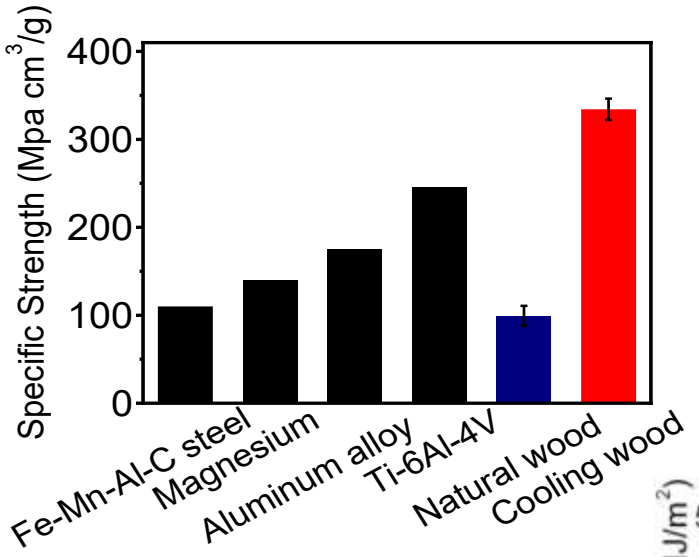


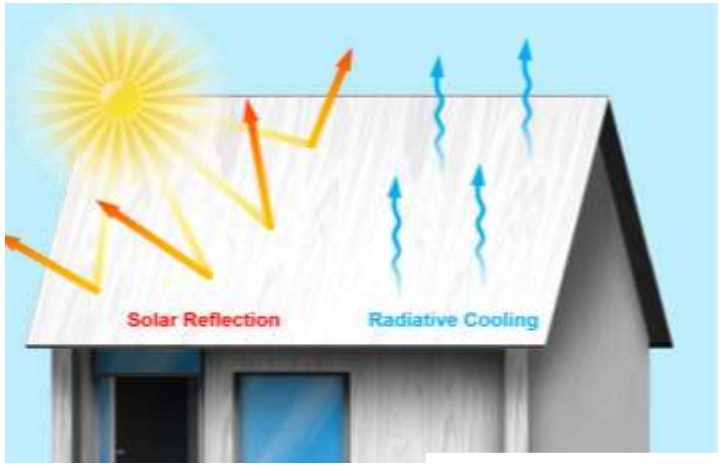


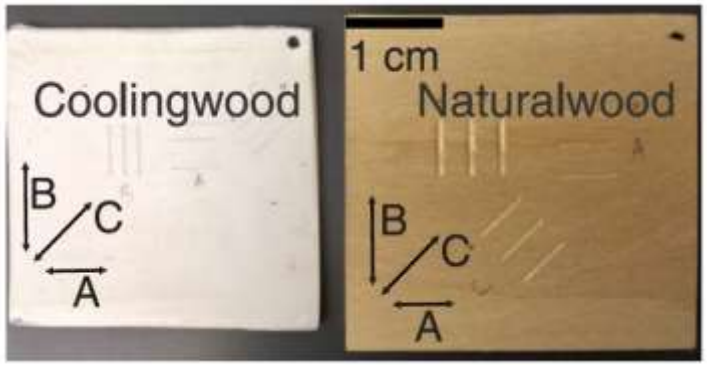
Science, 2019, 364, 760

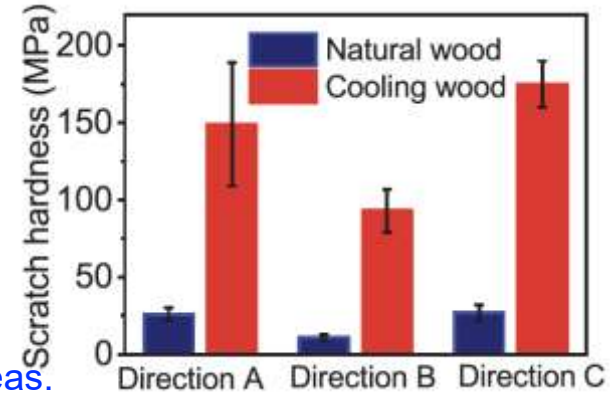
Cooling Wood: A Structural Material for Building

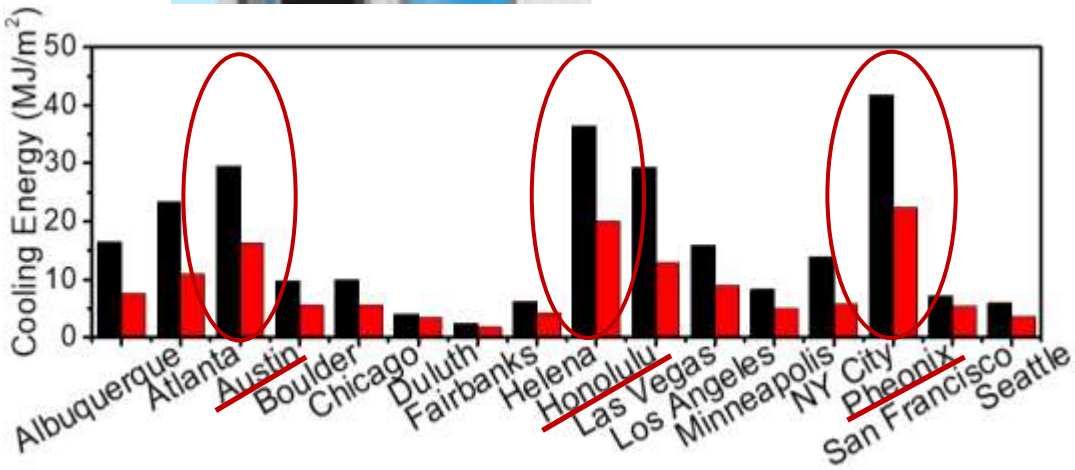












- More effective radiation cooling in dry areas.
- Cooling savings of 35% and 22% for buildings built before and after 1980, respectively.

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The super-cool materials that send heat to space

Modeling:

- Through collaboration with Prof. Jelena Srebric
- EnergyPlus version 8
- Midrise apartment buildings across the United States, based on data from old (built before 1980) and new (built after 2004) structures provided by the U.S. Department of Energy Commercial Reference Buildings

Transparent Wood: Fun Fact (YouTube, 24M Views in 4 Years)

https://www.youtube.com/watch?v=uUU3jW7Y9Ak



Making transparent wood

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ARTICLE | March 4, 2016

Optically Transpa
Functional and St

Yuanyuan Li, Qiliang Fu, Shun Y

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Abstract

Optically transparent wood
and haze of 71% was obta
template. The template wa
lignin component, creating
Transparent wood was pre
and the nanoscale cellulos
refractive-index-matched p
During the process, the hie
Optical properties of TW a
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potential candidate for ligh
buildings and transparent

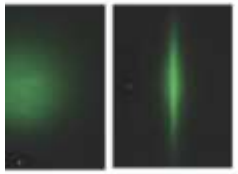
RIALS

od Composites

onggang Yao, Wei Luo,

d: January 24, 2016
ised: March 5, 2016
online: May 4, 2016

arent wood composites are
al wood. These wood composites
bit dramatically different optical



Super Wood: Fun Fact (YouTube, 11M Views in 2 Years)

Published: 08 February 2018

https://www.youtube.com/watch?v=CgINRNrMFGM

Processing bulk natural wood into a high-performance structural material

Jianwei Song, Chaoji Chen, Shuze Zhu, Mingwei Zhu, Jiaqi Dai, Upamanyu Ray, Yiju Li, Yudi Kuang, Yongfeng Li, Nelson Quispe, Yonggang Yao, Amy Gong, Ulrich H. Leiste, Hugh A. Bruck, J. Y. Zhu, Azhar Vellore, Heng Li, Marilyn L. Minus, Zheng Jia, Ashlie Martini, Teng Li & Liangbing Hu

Nature **554**, 224–228 (2018) | Cite this article

Transformation de bois naturel brut en un matériau de gros œuvre

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NileRed

Making bulletproof wood

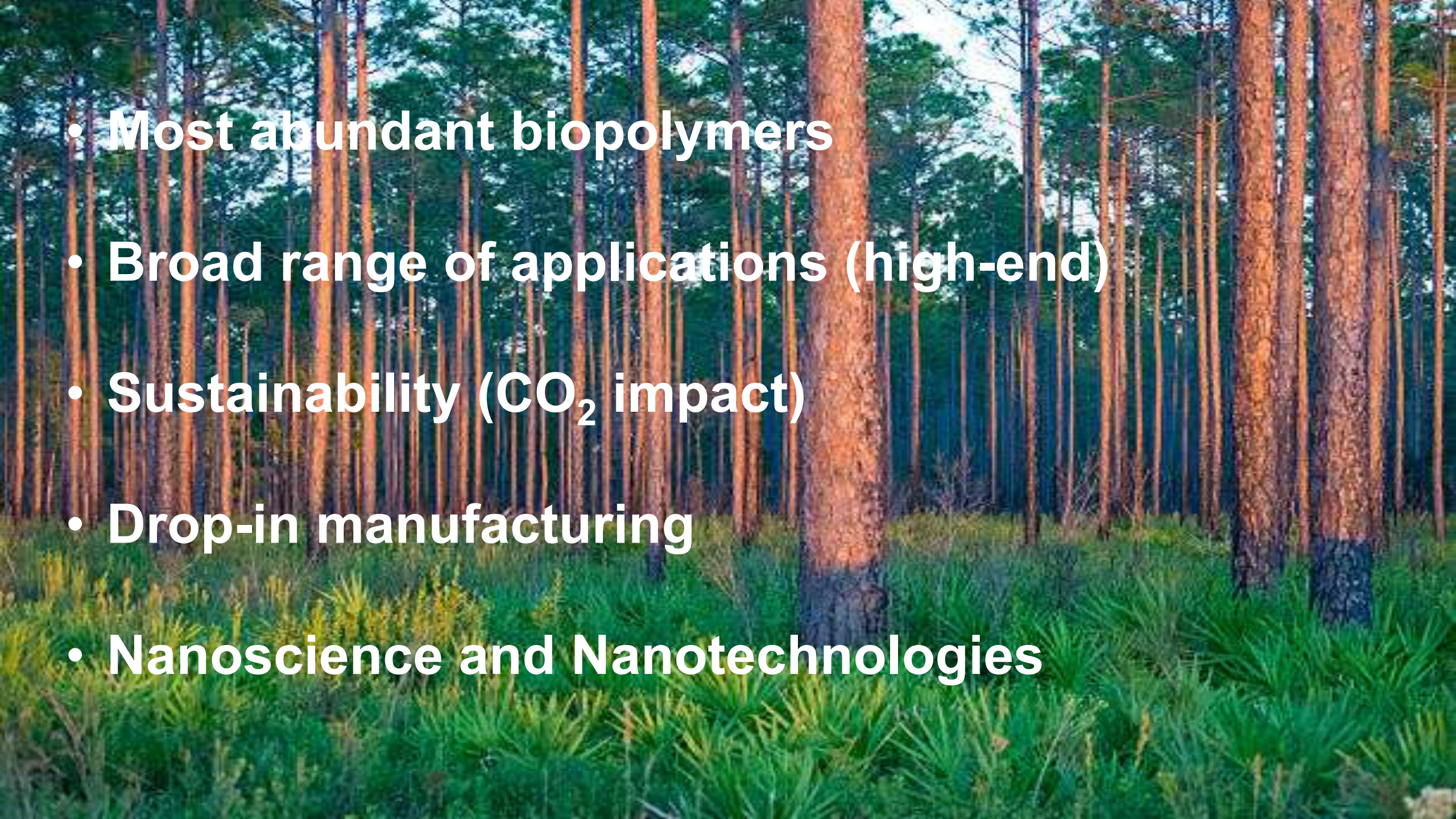
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Back in 2020, I read a paper that claimed that bulletproof wood might be possible. The moment that I saw this, I felt that I had to test it myself and I spent the ...more



- Most abundant biopolymers
- Broad range of applications (high-end)
- Sustainability (CO_2 impact)
- Drop-in manufacturing
- Nanoscience and Nanotechnologies