Extrusion-Based 3D Printing of Particulate Wood-Thermoset Composites for Construction Applications

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Univ. of Maine. Orono, ME

University of Idaho
AUBURN UNIVERSITY

Motivation

- Reduced Material Costs, and Cheaper Construction
- Quicker Construction, Design flexibility, and Improved Form
- Eco-friendly, improved sustainability, scalable, Efficient, New Markets

Hypothesis and Objective

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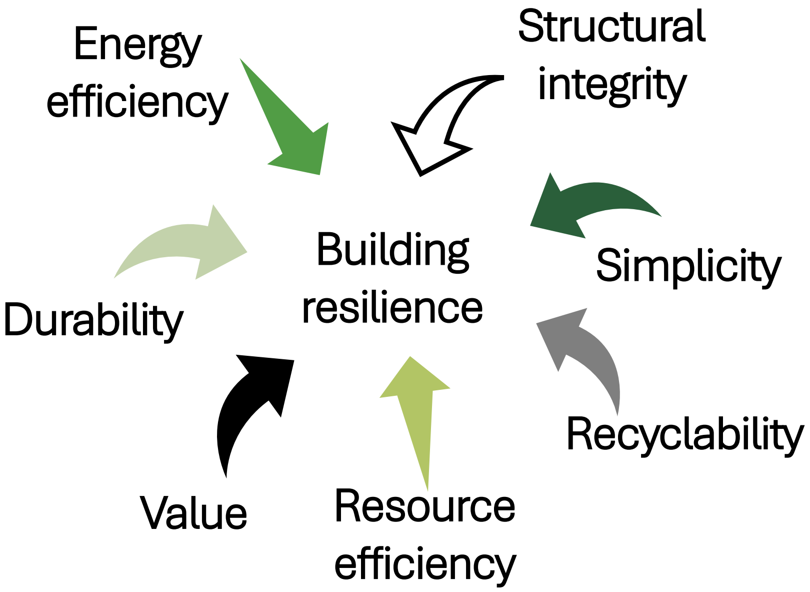
- **Our central hypothesis** is that a renewable, sustainable, and recyclable bio-based building construction material can be developed that will create affordable and resilient housing.
- **Our overall objective** is to develop the science, technology, and educational framework to underpin a democratized construction economy with building structures that are more durable, higher performing, and made from materials that are completely recoverable as a feedstock to repeat the process without virgin materials.



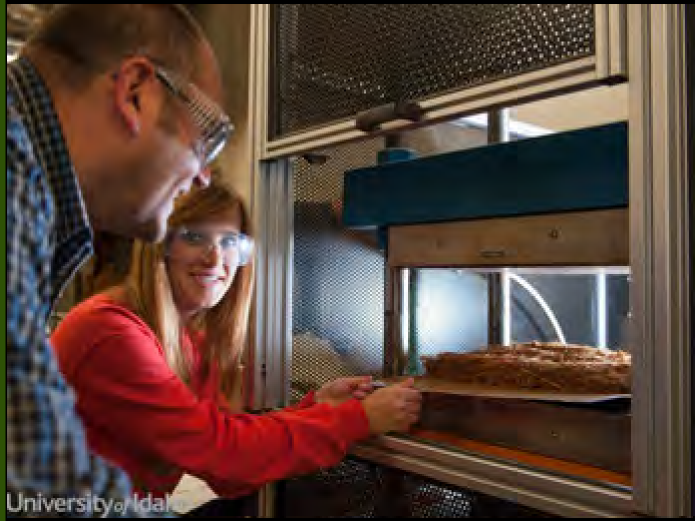
Our Team

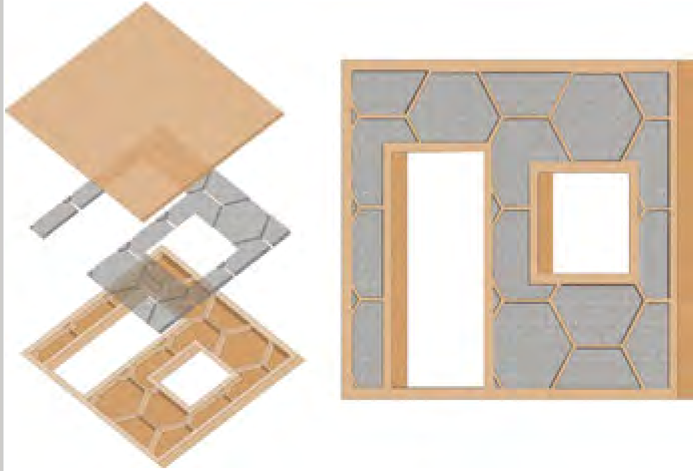
<u>PI</u>
Michael Maughan: Associate Professor, University of Idaho

<u>Co-PIs</u>
Lili Cai: Assistant Professor, University of Idaho
Ahmed Ibrahim: Associate Professor, University of Idaho
Carolina Manrique: Associate Professor, University of Idaho
Brian Via: Professor, Auburn University

<u>Senior Personnel</u>
Sushil Adhikari: Professor, Auburn University
Maria Auad: Professor, Auburn University
Audrey Fu: Associate Professor, University of Idaho
Armando McDonald: Professor, University of Idaho
M. Soledad Peresin: Associate Professor, Auburn University
Daniel Robertson: Associate Professor, University of Idaho
Randall Teal: Professor, University of Idaho
Damon Woods: Assistant Research Professor, University of Idaho

<u>Industry Partner</u>
Shayne Kimball: Owner, Kimball Farms



Challenges

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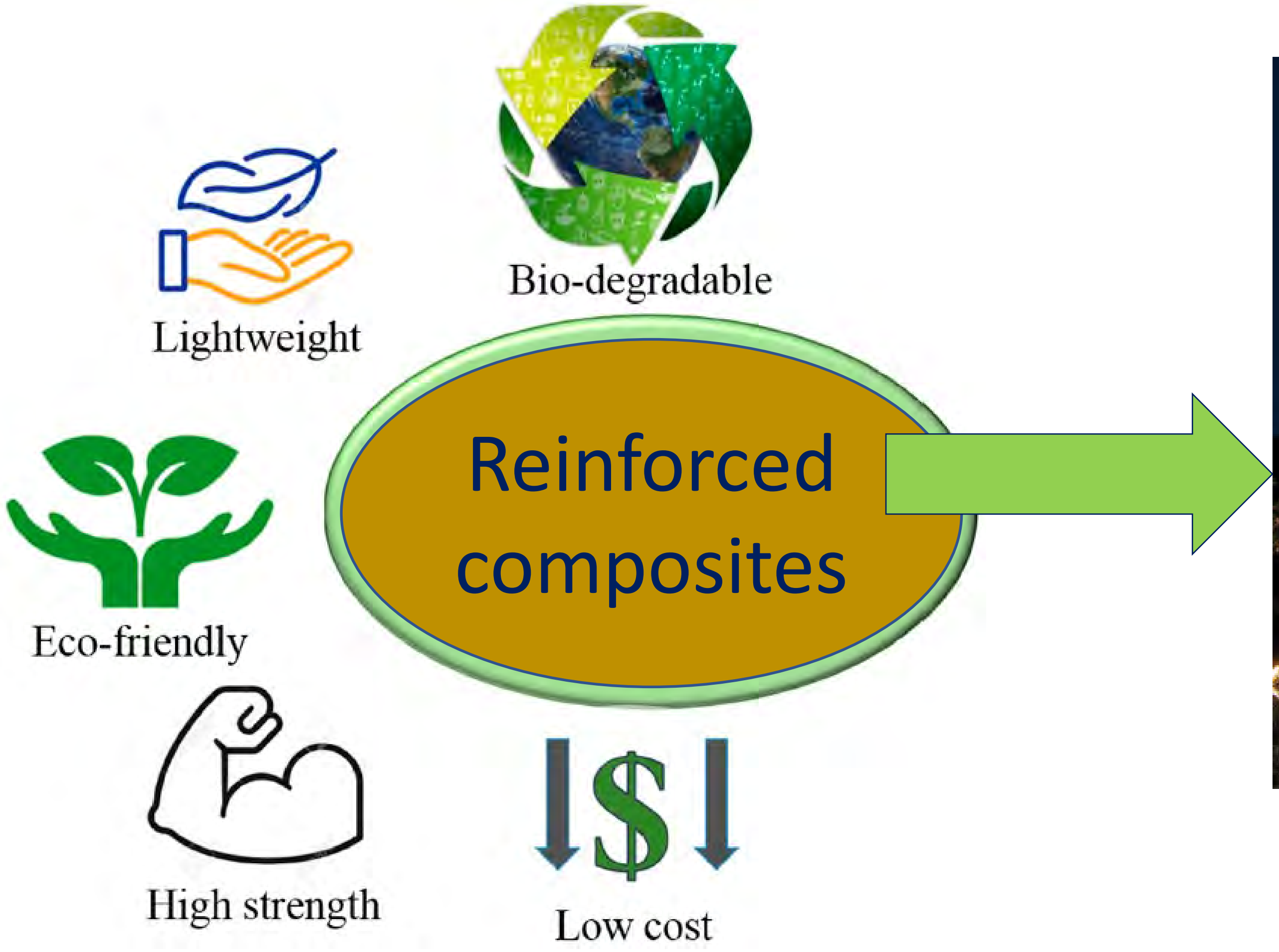
- Aim 1 - Design and Synthesize High-Performance Bio-resins with Controlled Macromolecular Architecture
- Aim 2 - Bio-based Additive Manufacturing Technology Development
- Aim 3 - PrinTimber Performance Evaluation, Improvement, Simulation, and Prediction
- Aim 4 - Cradle-to-Cradle Design

Objective

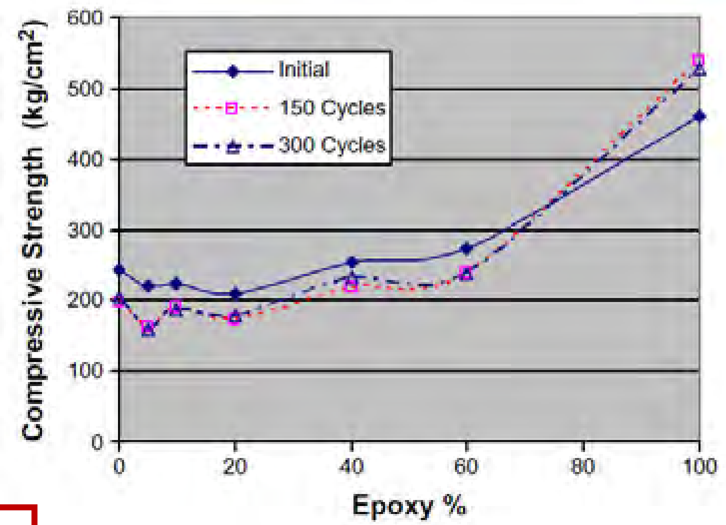
- Prepare nanocellulose reinforced thermoset composites for three-dimensional print (3D print) building assemblies utilizing cellulose nanofibers.



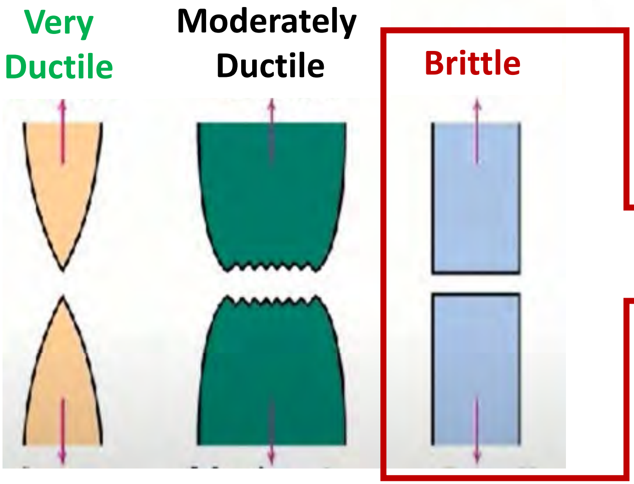
Resin systems

A) Epoxy resin

- ❑ High mechanical strength
- ❑ Resistance to moisture and chemical attacks
- ❑ Appreciable resilience
- ❑ Excellent abrasion properties
- ❑ Good electrical insulating quality
- ❑ Adjustable curing process



Appearance	Colourless to Pale Yellow Liquid
Flexural strength (MPa)	40–67
Specific gravity (kg/m^3)	1120–1210
Viscosity at 25 °C (kg/m s)	0.25–0.75
Heat distortion temperature (°C)	50
Solid content (%)	84
Modulus of elasticity (MPa)	3100 to 3800
Tensile strength (MPa)	90 to 120
Max percentage elongation (%)	4
Impact strength (kg/m^2)	9
Glass transition temperatures	150 to 220 °C



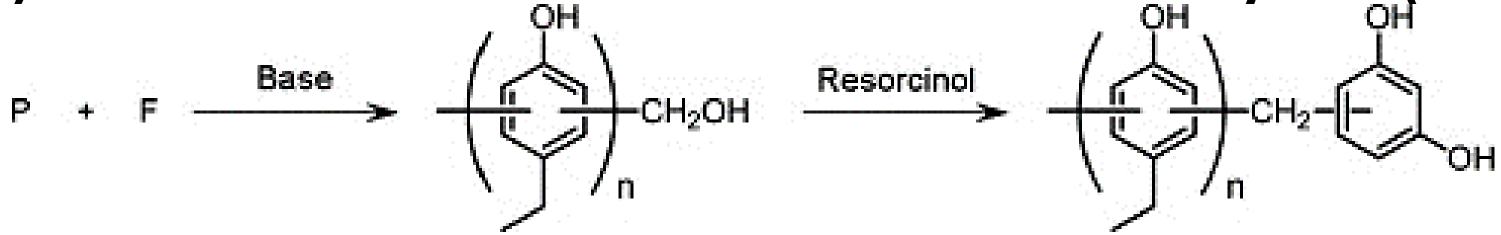
Cellulose nanofiber

toughening/strengthening agent to enhance the properties of epoxy resin in structural applications

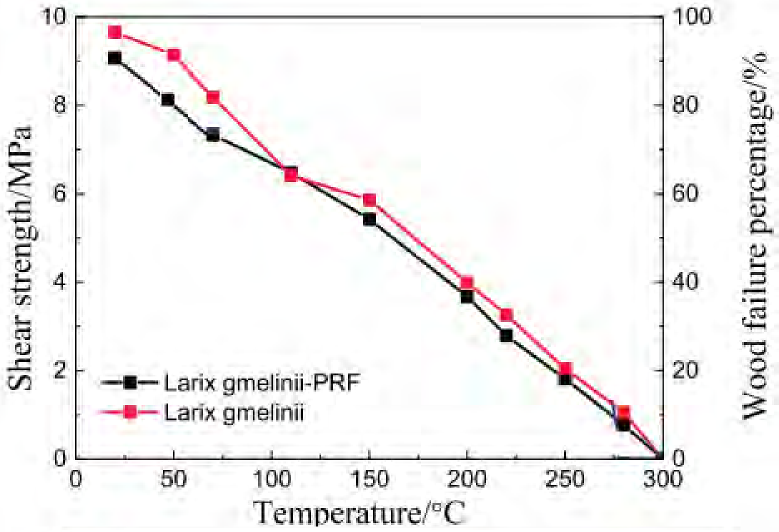
El-Hawary, M. M., & Abdul-Jaleel, A. (2010). *Construction and building materials*, *24*(8), 1523-1528.

Resin systems cont’

B) Phenol-Resorcinol- Formaldehyde (PRF) resin



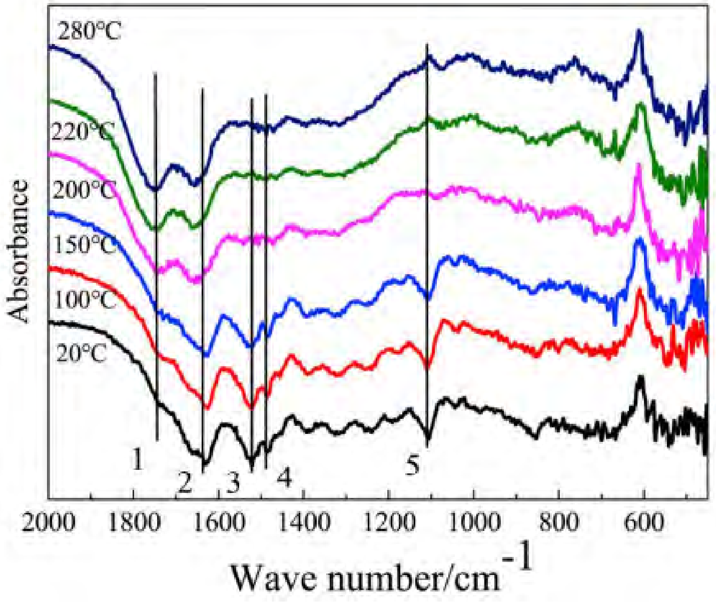
- Structural beams
- High mechanical strength
- Weather resistance under a variety of climatic conditions
- Satisfy exterior use requisites
- Adjustable curing process



- Brittle in nature
- Susceptible to the elevated temperatures

Cellulose nanofiber

Toughening/strengthening agent to enhance the properties for structural applications

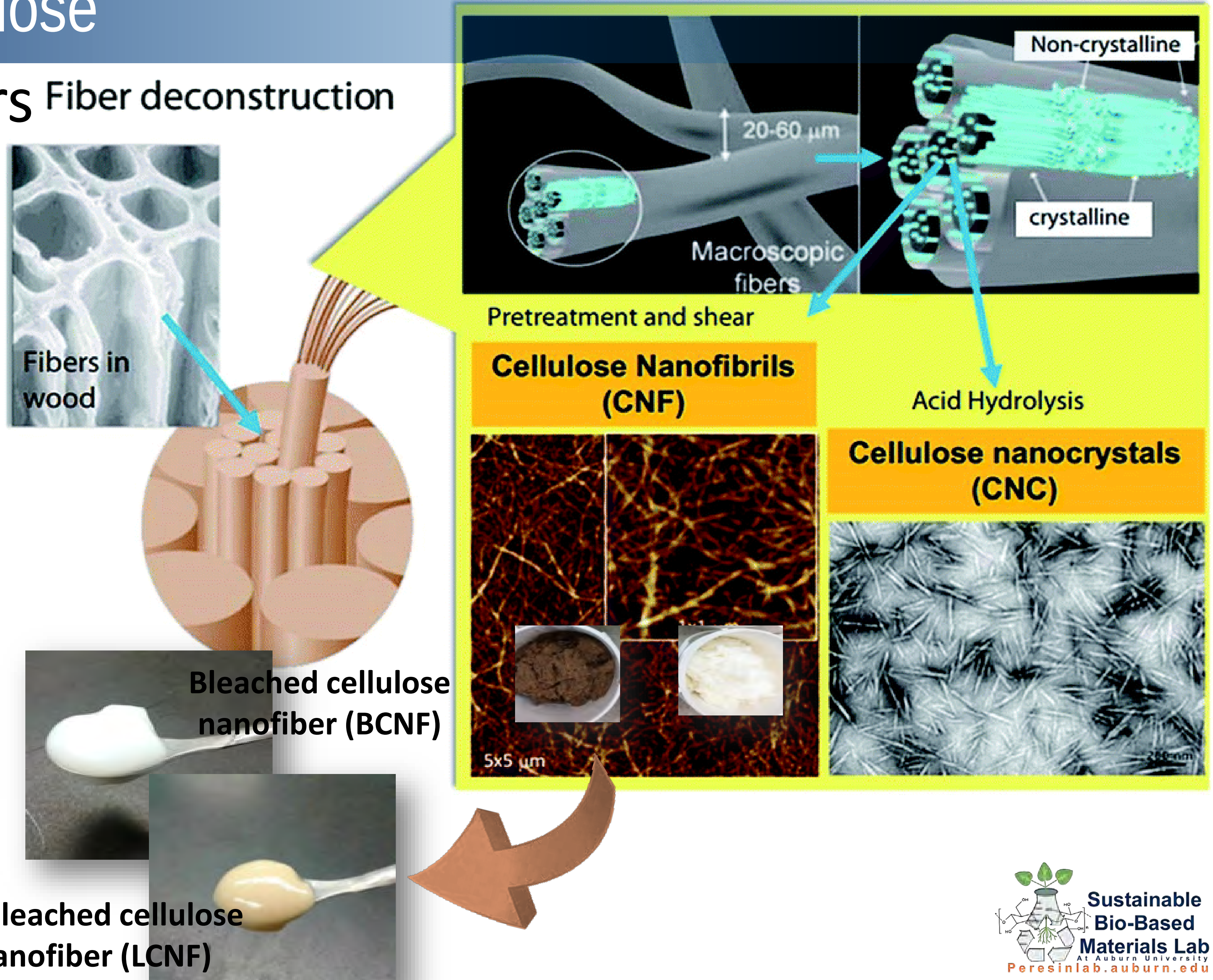


Pilato, L. (2013) Reactive and functional polymers, 73(2), 270-277.
Liu, J., Yue, K., Xu, L., Wu, J., Chen, Z., Wang, L., ... & Lu, W. (2020). International Journal of Adhesion and Adhesives, 98, 102500.

“Highly refined” cellulose

Cellulose nanofibers

Fiber deconstruction



Thakur, V., Guleria, A., Kumar, S., Sharma, S., & Singh, K. (2021). *Materials Advances*, *2*(6), 1872-1895.

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Introduction cont'

Softwood off cuts

Mixed wastes

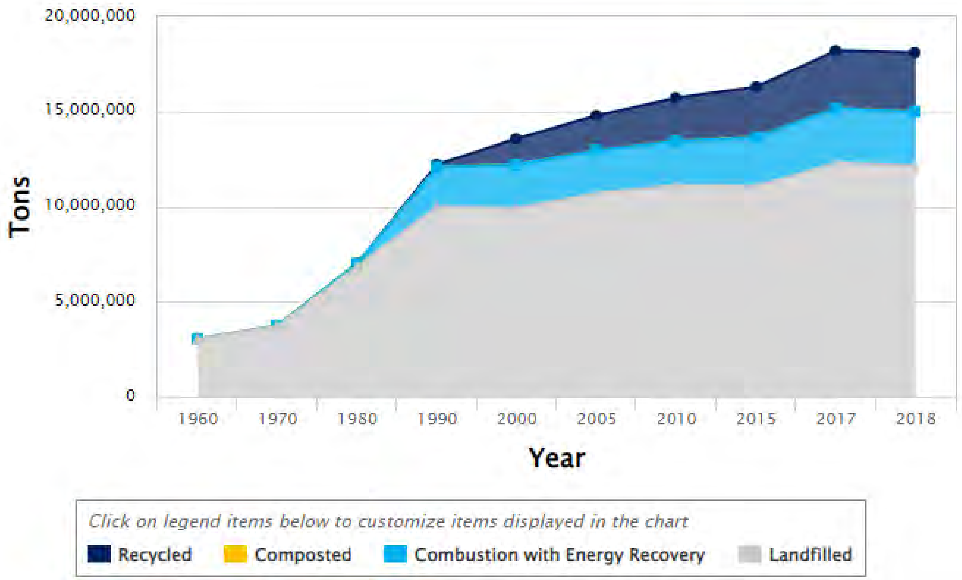
Hardwood wastes

Wood Shavings

Off cuts

Saw dust

Residues from different wood industries



Jahan, I., Zhang, G., Bhuiyan, M., & Navaratnam, S. (2022). *Sustainability*, *14*(17), 10478.

Research plan

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Step 1

Cellulose nanofiber production

- ❑ Chemical composition
- ❑ Thermal stability
- ❑ Colloidal stability
- ❑ Morphology

Step 2

Cellulose nanofiber – reinforced thermoset composites

- ❑ Interfacial interactions
- ❑ Chemical characterization
- ❑ Thermal behavior
- ❑ Mechanical performance
- ❑ Morphological properties

Step 3

Optimization of the process parameters for wood-thermoset extrusion

- ❑ Mechanical performance
- ❑ Dimensional stability
- ❑ Fire resistance
- ❑ Surface quality

Step 4

Cellulose nanofiber – reinforced thermoset wood extrudates

- ❑ Mechanical performance
- ❑ Dimensional stability
- ❑ Fire resistance
- ❑ Surface quality

Materials and methods

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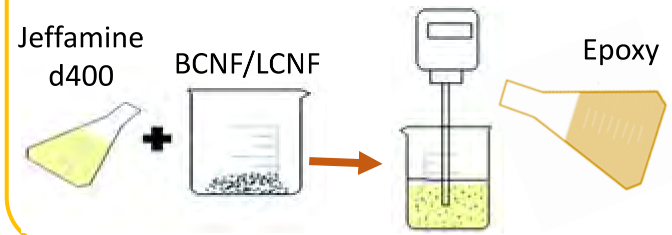
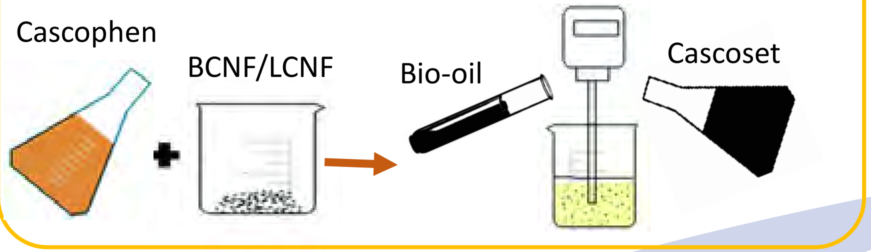
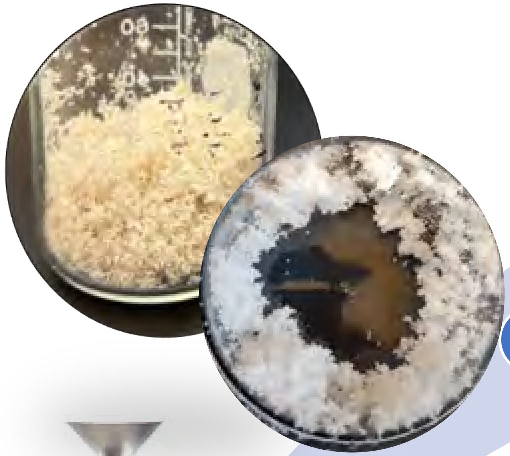
Epoxy composite



Phenol-resorcinol-Formaldehyde composite

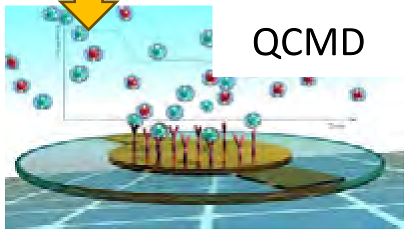




Mechanical fibrillation

Bleached and unbleached CNF

BCNF/LCNF reinforced thermoset



QCMD

Mixed with wood flour

Under 40 mesh

- ❑ Screw speed
- ❑ Wood: resin
- ❑ Wood particle size

Extrude

Results from Step 2

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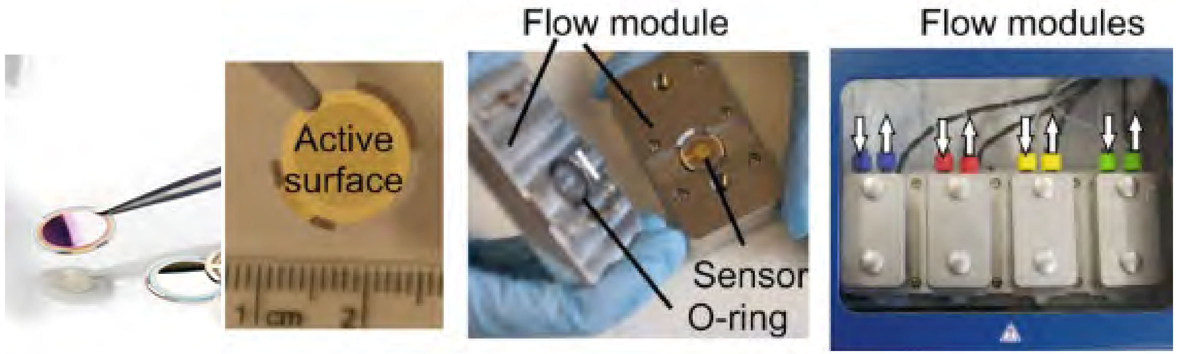
Cellulose nanofiber – reinforced Thermoset composites

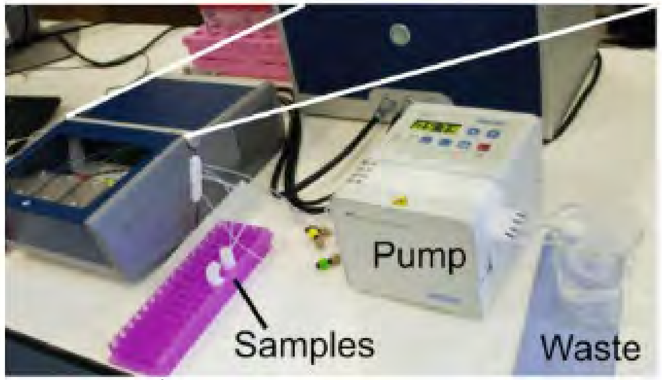
- ❑ Interfacial interactions
- ❑ Chemical characterization
- ❑ Mechanical performance
- ❑ Morphological properties

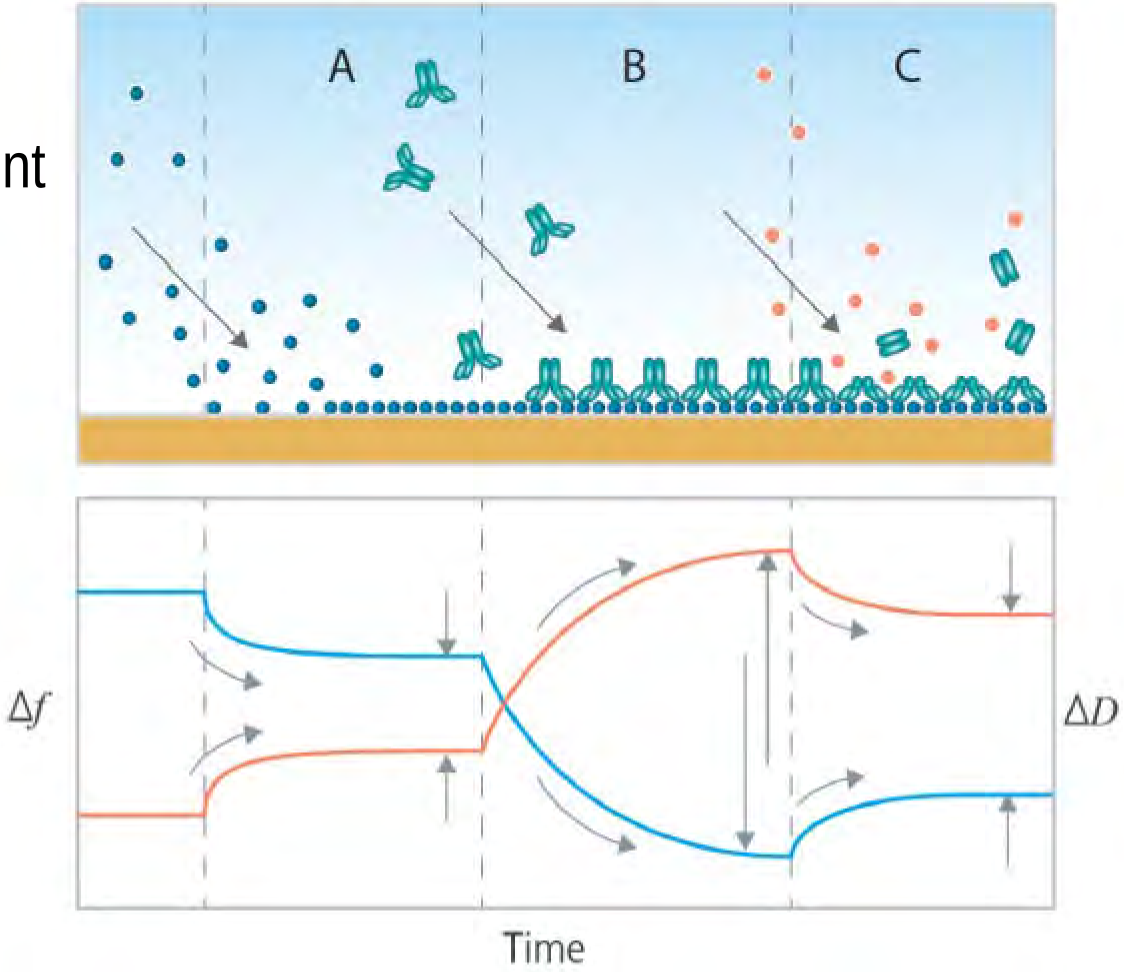
Interfacial Interactions

Quartz Crystal Microbalance with Dissipation (QCMD)

Surface interactions of cellulose nanofibers (CNF) of different chemical compositions with thermoset resins







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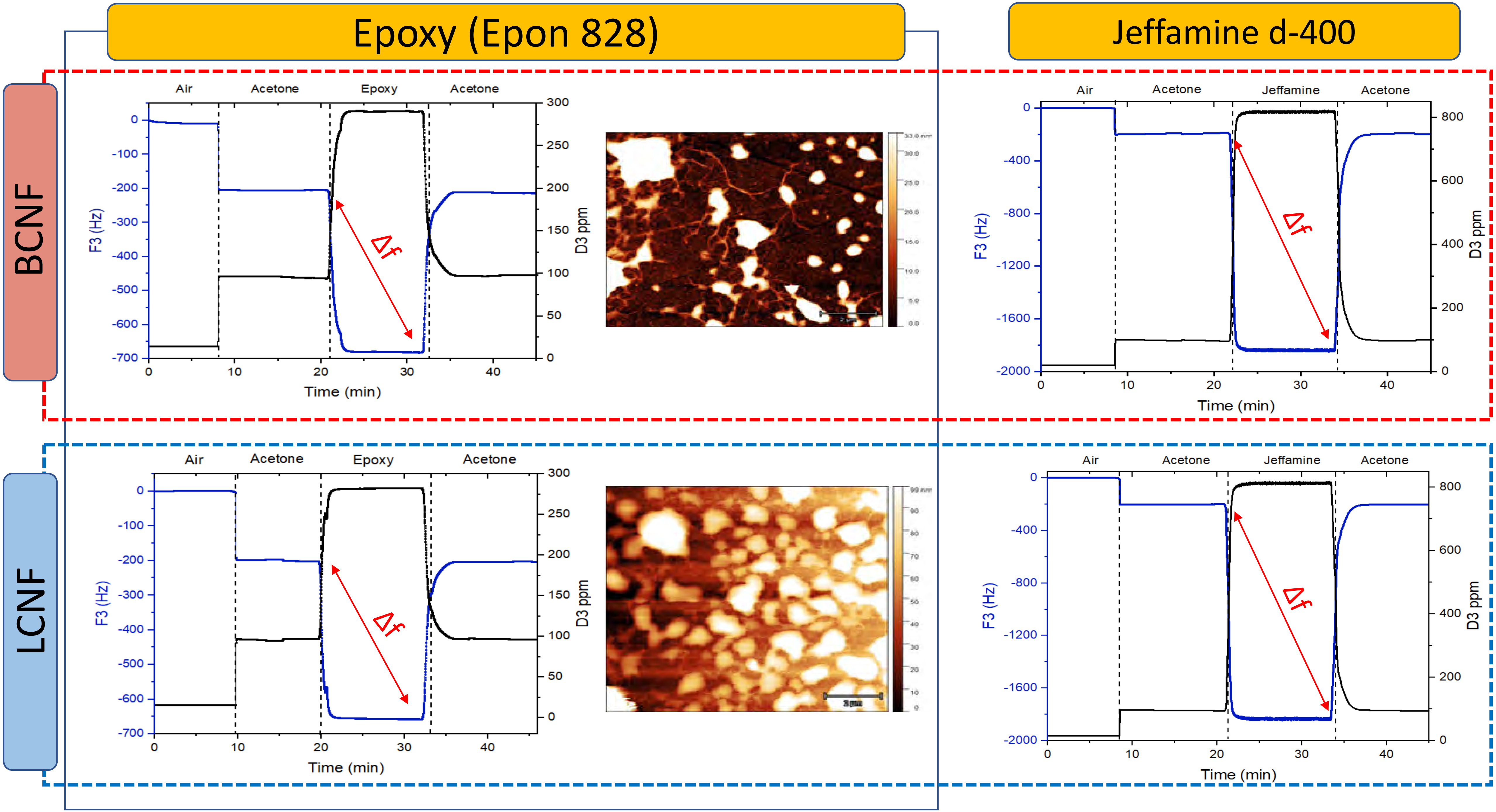
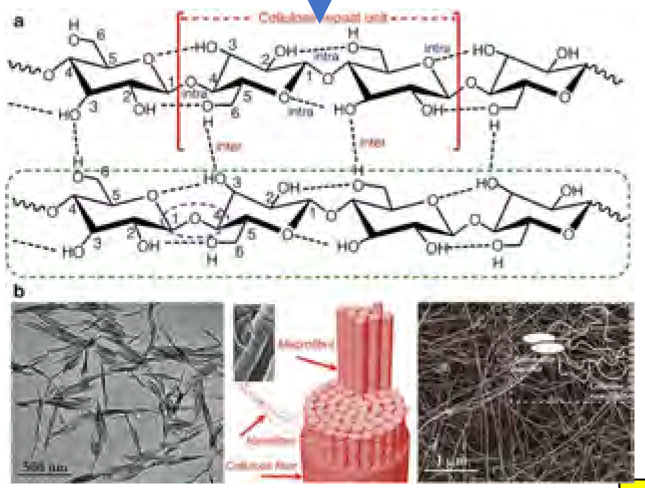
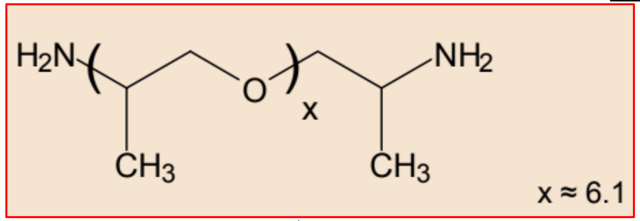


Epoxy (Epon 828)
Jeffamine d-400
BCNF
LCNF
Air
Acetone
Epoxy
Acetone
Jeffamine
Δf
F3 (Hz)
D3 ppm
Time (min)

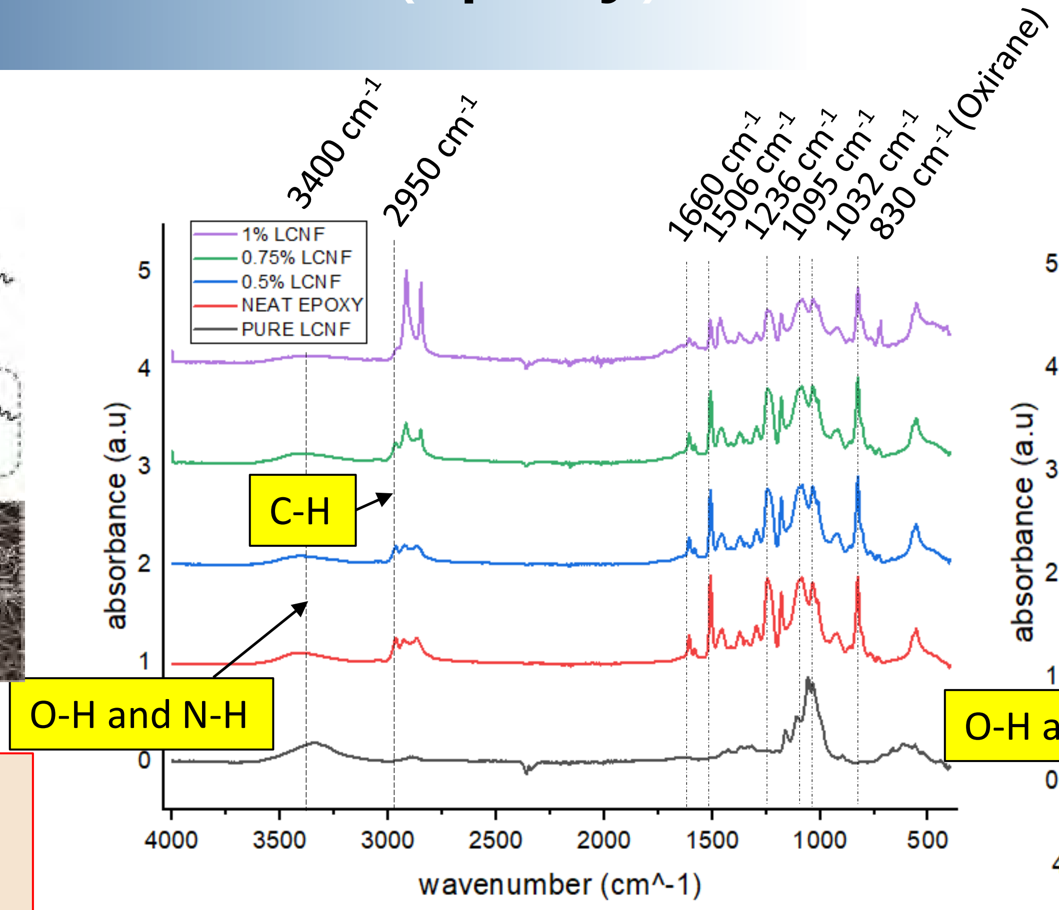
Chemical characterization (epoxy)

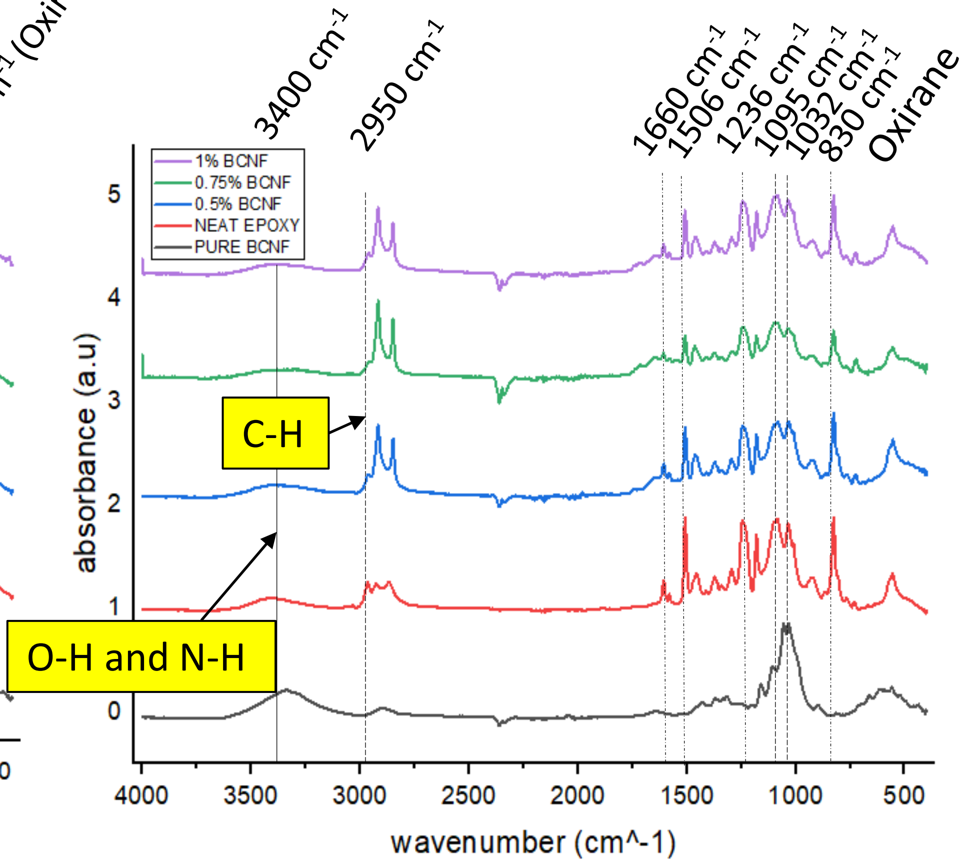
Cellulose nanofiber

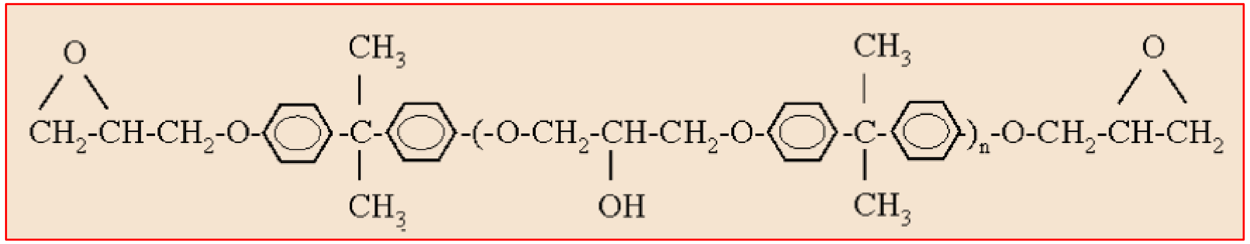




Jeffamine d-400







Epon 828

Zhang, K., Barhoum, A., Xiaoqing, C., Li, H., & Samyn, P. (2019). In *Handbook of nanofibers* (pp. 409-449). Springer, Cham.
Nuruddin, M., Hosur, M., Mahdi, T., & Jeelani, S. (2017). Sensors & Transducers, 210(3), 1.

Mechanical properties of epoxy nano-composites

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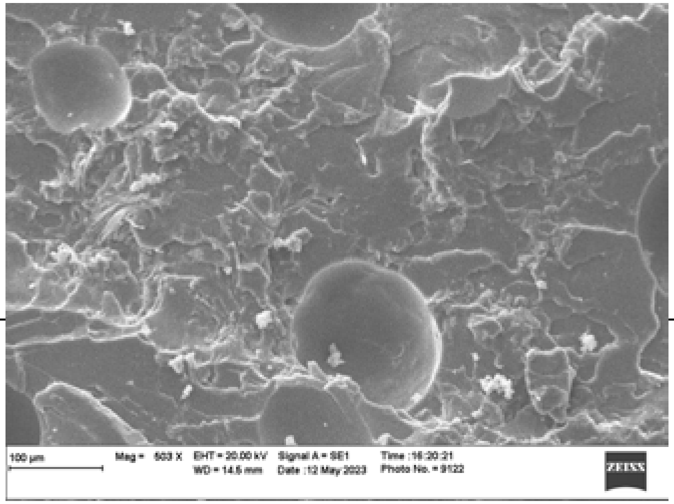
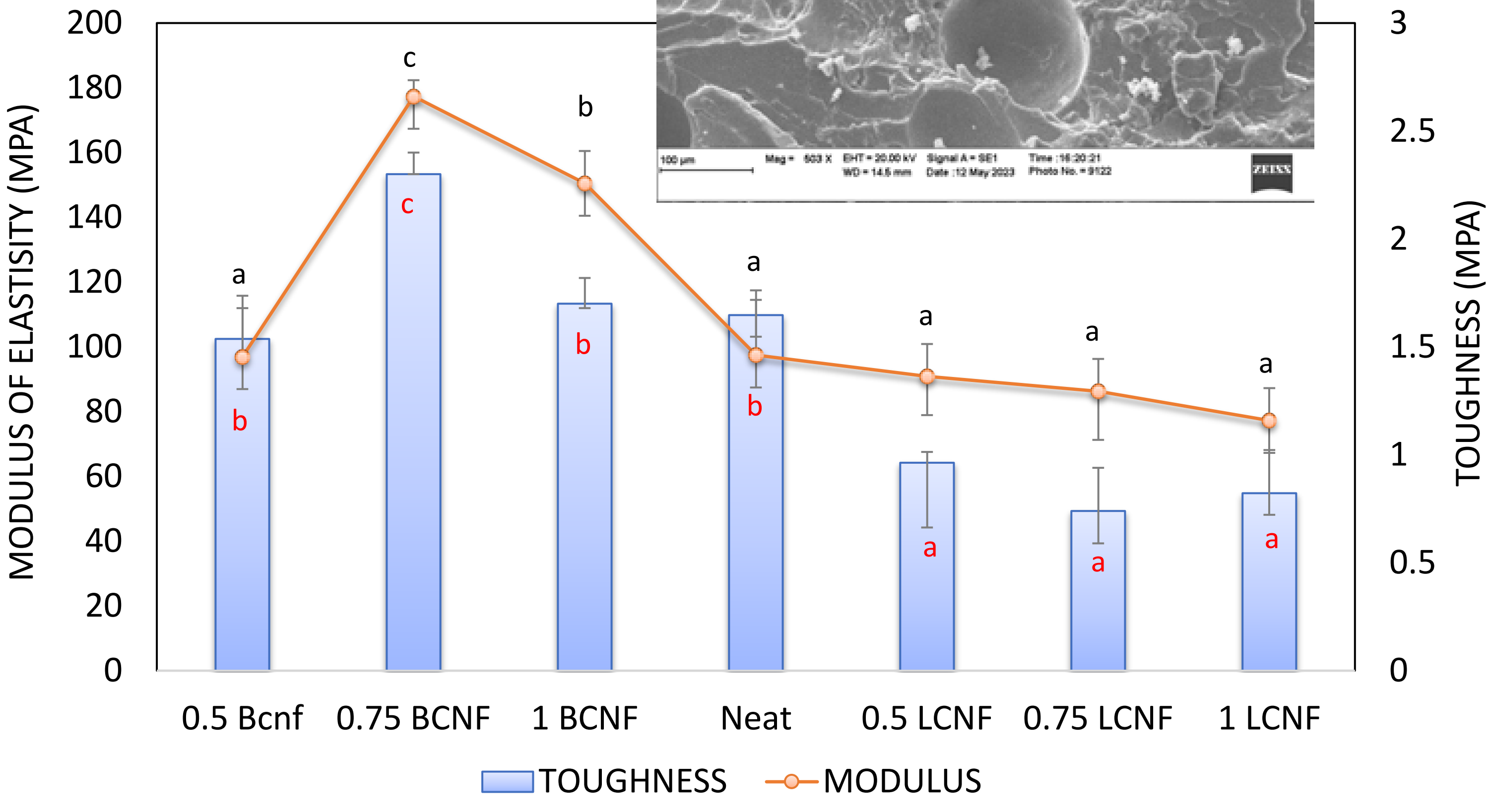
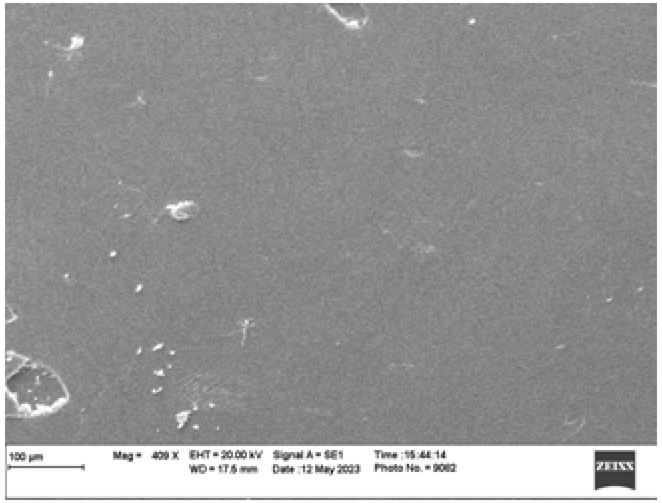
LCNF reinforced epoxy

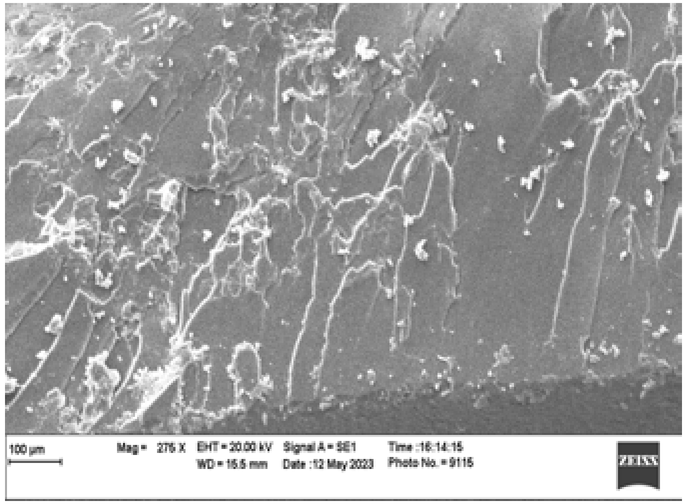




Neat epoxy



BCNF reinforced epoxy



BCNF/LCNF interfacial interactions with PRF

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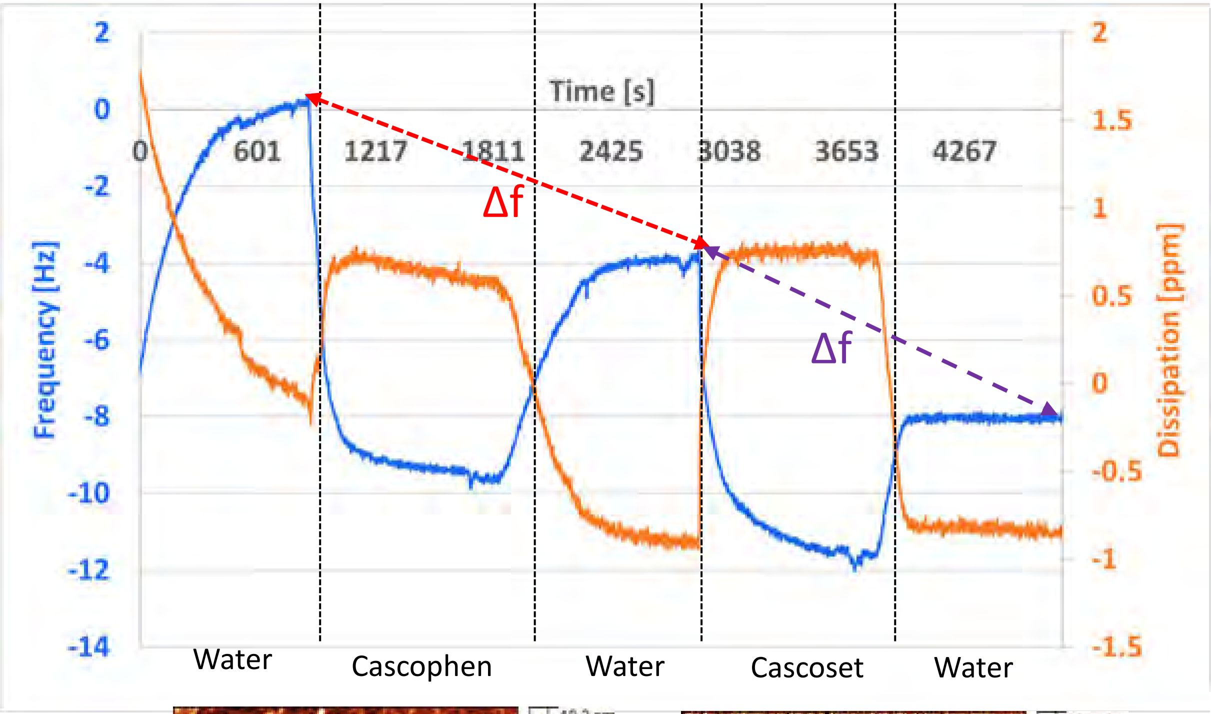
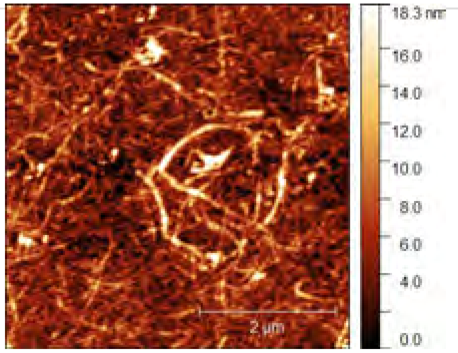
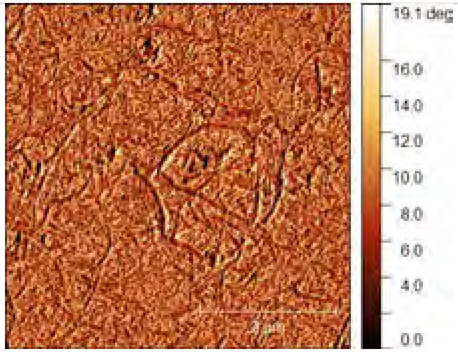
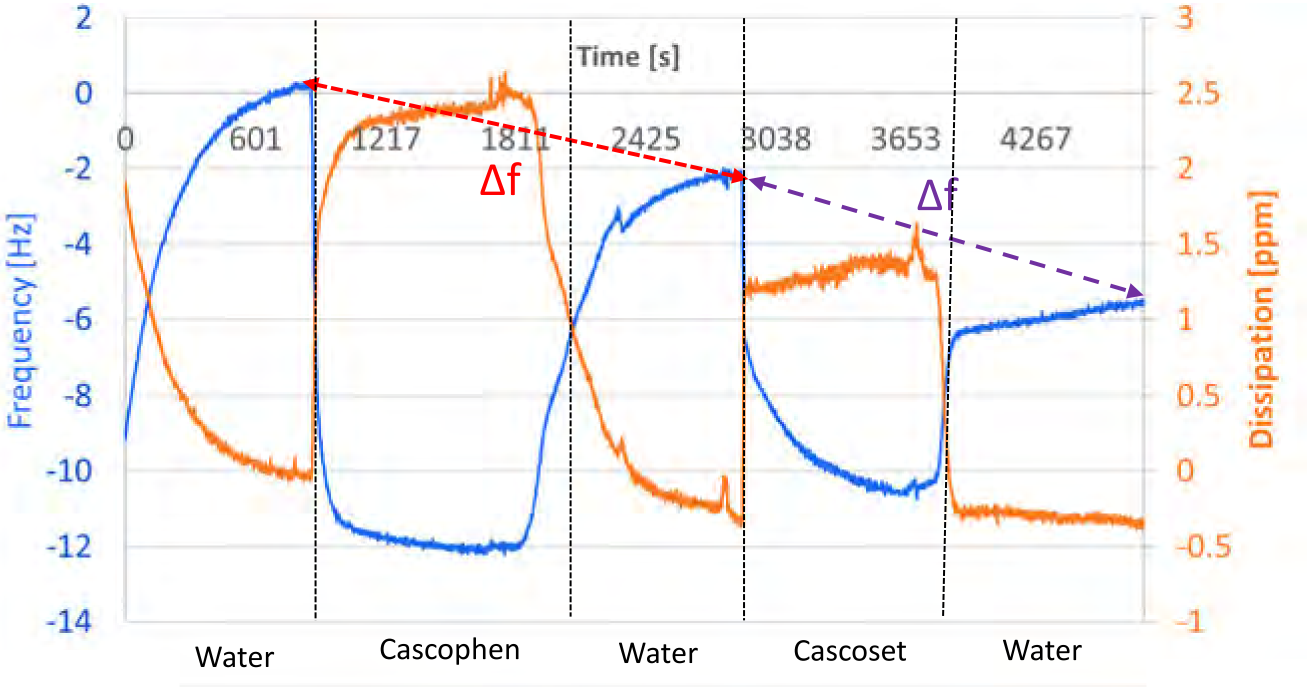
BCNF

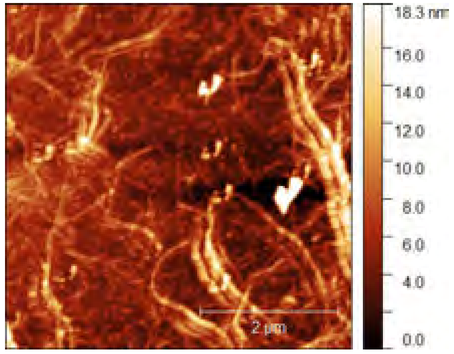


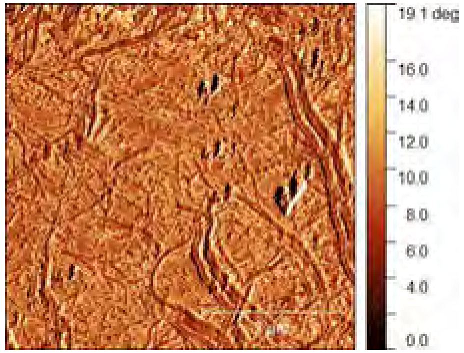




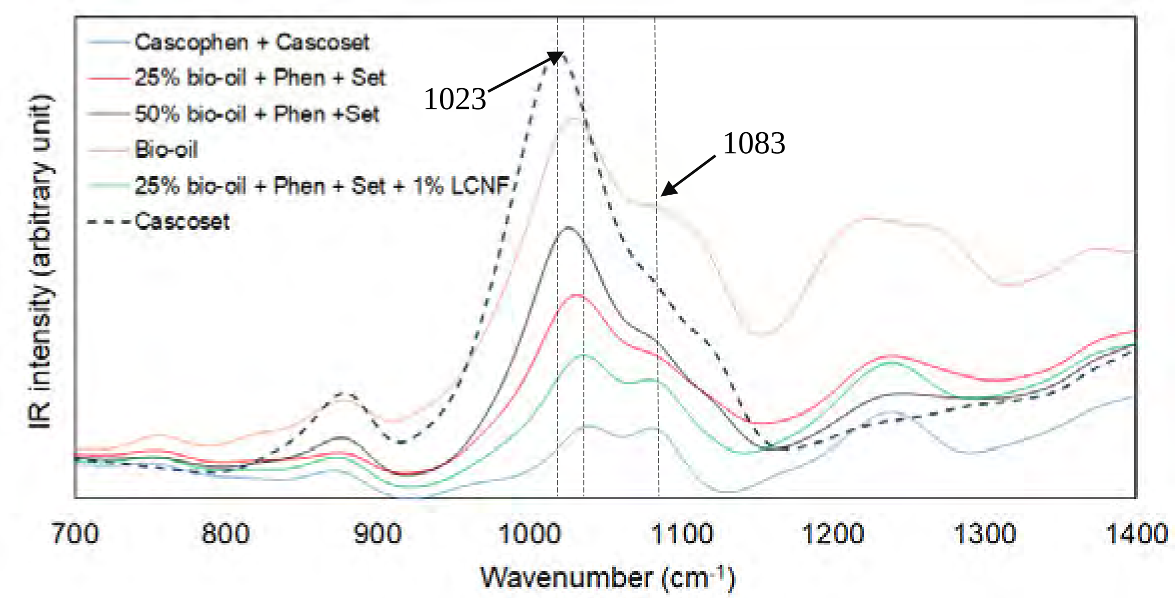
LCNF

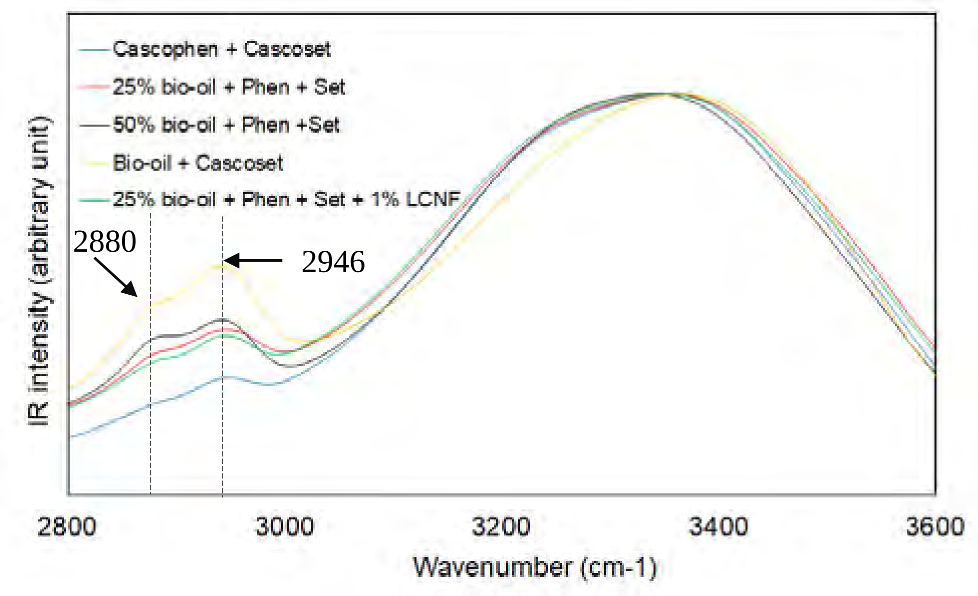




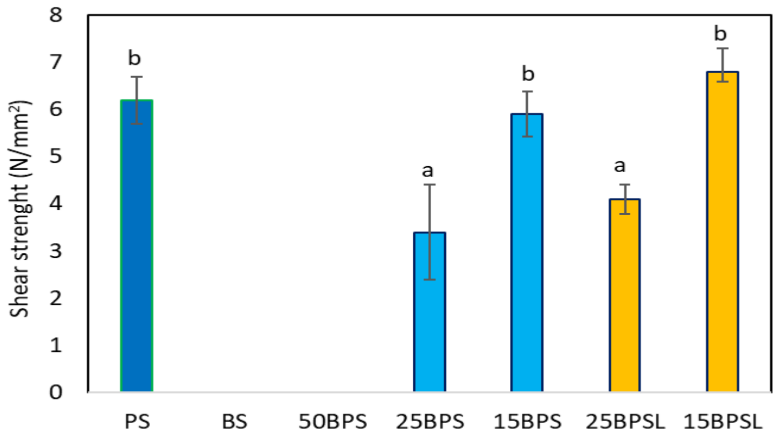


Chemical composition and mechanical performance of different **PRF** composites





Phen + Set (PS)
Bio-oil + Set (BS)
50% Bio-oil + Phen +Set (50BPS)
25% Bio-oil + Phen + Set (25BPS)
15% Bio-oil + Phen + Set (15BPS)
25% Bio-oil + Phen + Set + 1% LCNF (25BPSL)
15% Bio-oil + Phen + Set + 1% LCNF (15BPSL)



Results from step 3

Optimization of the process parameters for **wood-neat resin extrusion**

Process Parameters

- Wood particle size
- Resin : Wood ratio
- Extruder's screw speed
- Resin: hardener ratios

Wood- Epoxy composites

I. Smaller particle size
II. Higher resin : wood
III. Medium extruder speed

Wood- PRF composites

I. 50:50 resin : wood
II. Low extruder speed
III. Low hardener: resin ratio

Step 4 Rheological properties of wood-epoxy after adding CNF

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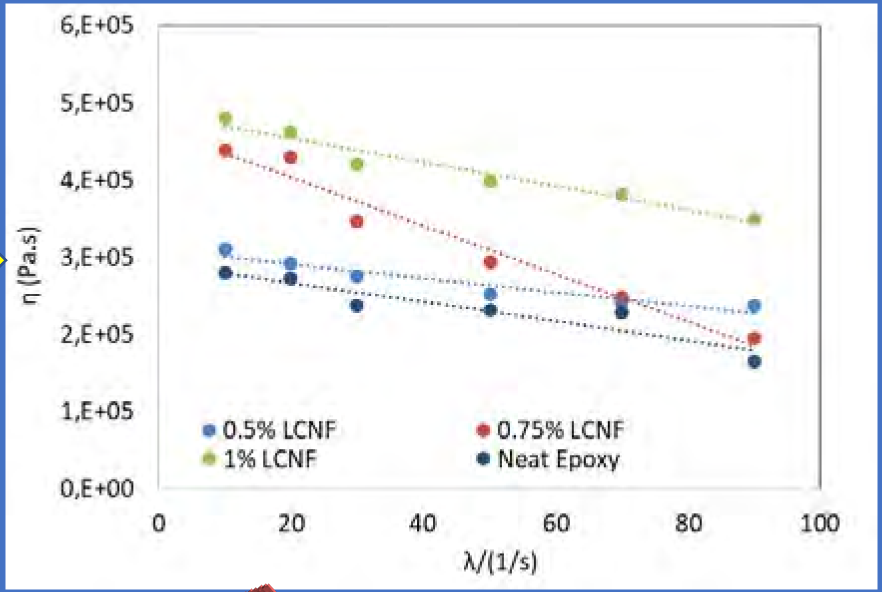
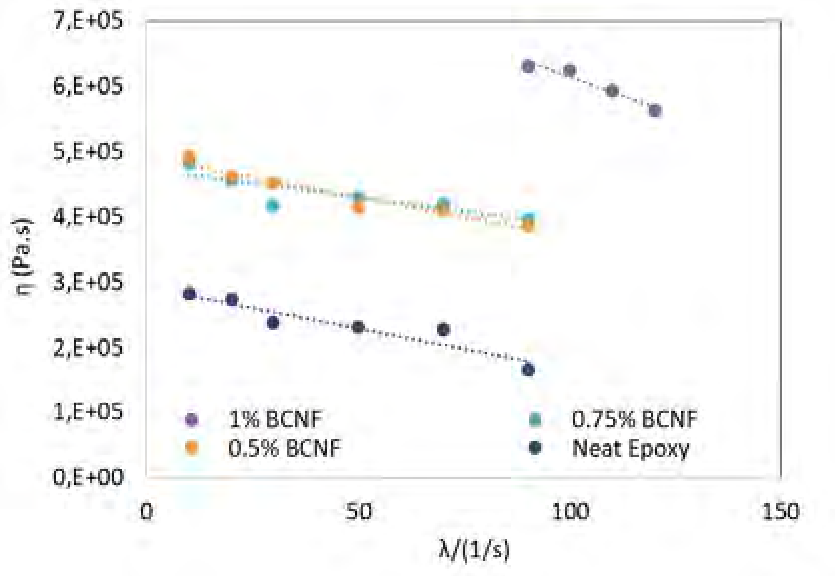
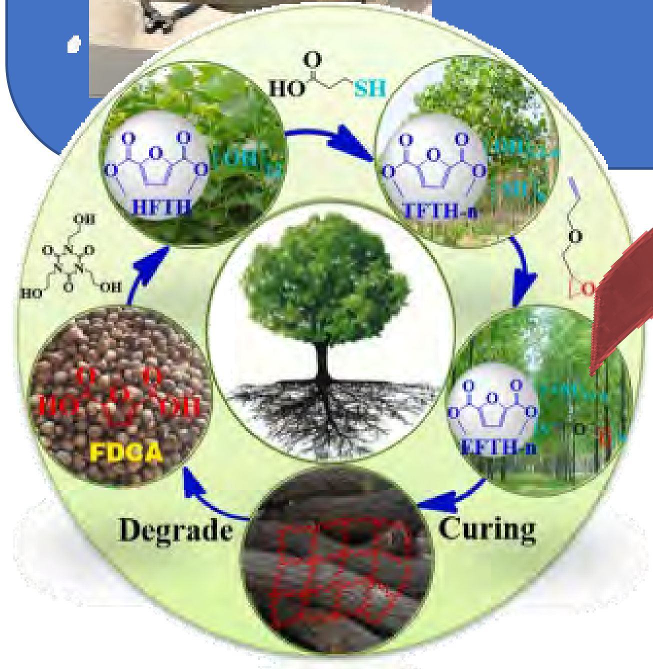
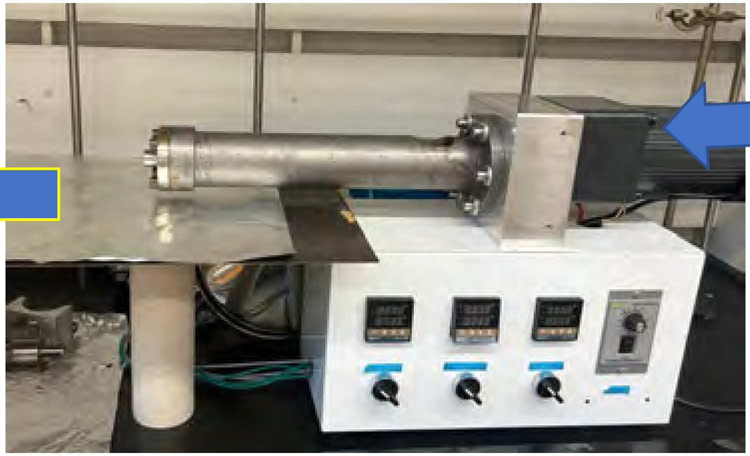






Bio-based resin

Nanocellulose reinforced epoxy composite



Conclusions

- The results from interfacial interaction and FTIR confirm that CNF may act as a curing catalyst during epoxy/PRF gelation and increases the cross-link density of the polymers while reducing curing time.

- Incorporating cellulose nanofiber changed the failure mode of epoxy/PRF composites from the brittle to more ductile which is promising for 3d printing of building materials.

- The optimum process parameters for wood-epoxy and wood-PRF composites were different.

- Incorporating cellulose nanofiber increased the viscosity of the wood-thermoset composites. The viscosity information is very crucial when choosing the extruding parameters.

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Thanks for your attention!!

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