The potential of bamboo for multi-use application

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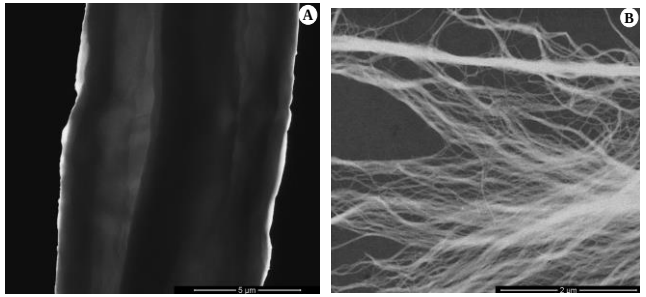
Bamboo research – BioSMat Group

- Processing and product development
- Physical/mechanical characterization
- Chemical/microstructural characterization
- Aging/Degradation
- Application

Cellulose

Fiber-cement composites

- ✓ Nanofibrilatted celulose
- ✓ Hybrid fiber-cement composite
- ✓ Filters



Natural culms

Bamboo poles

- ✓ Structural use
- ✓ Preservative treatment
- ✓ Standardization

Particles / Strands / Strips

Engineered bamboo

- ✓ Particleboards
- ✓ OSB
- ✓ Densified bamboo

Building materials

Bamboo research – BioSMat Group

- Development (process)
- Physical/mechanical prop.
- Chemical/microstructural prop.
- Aging/Degradation
- Application

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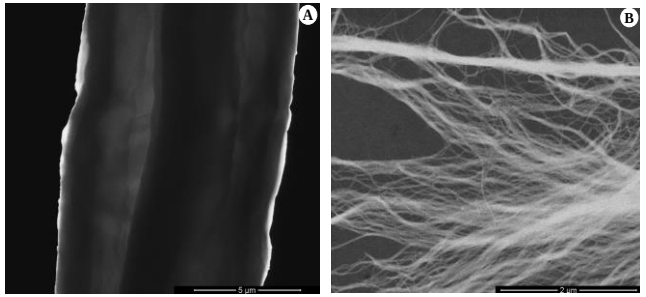

Natural form

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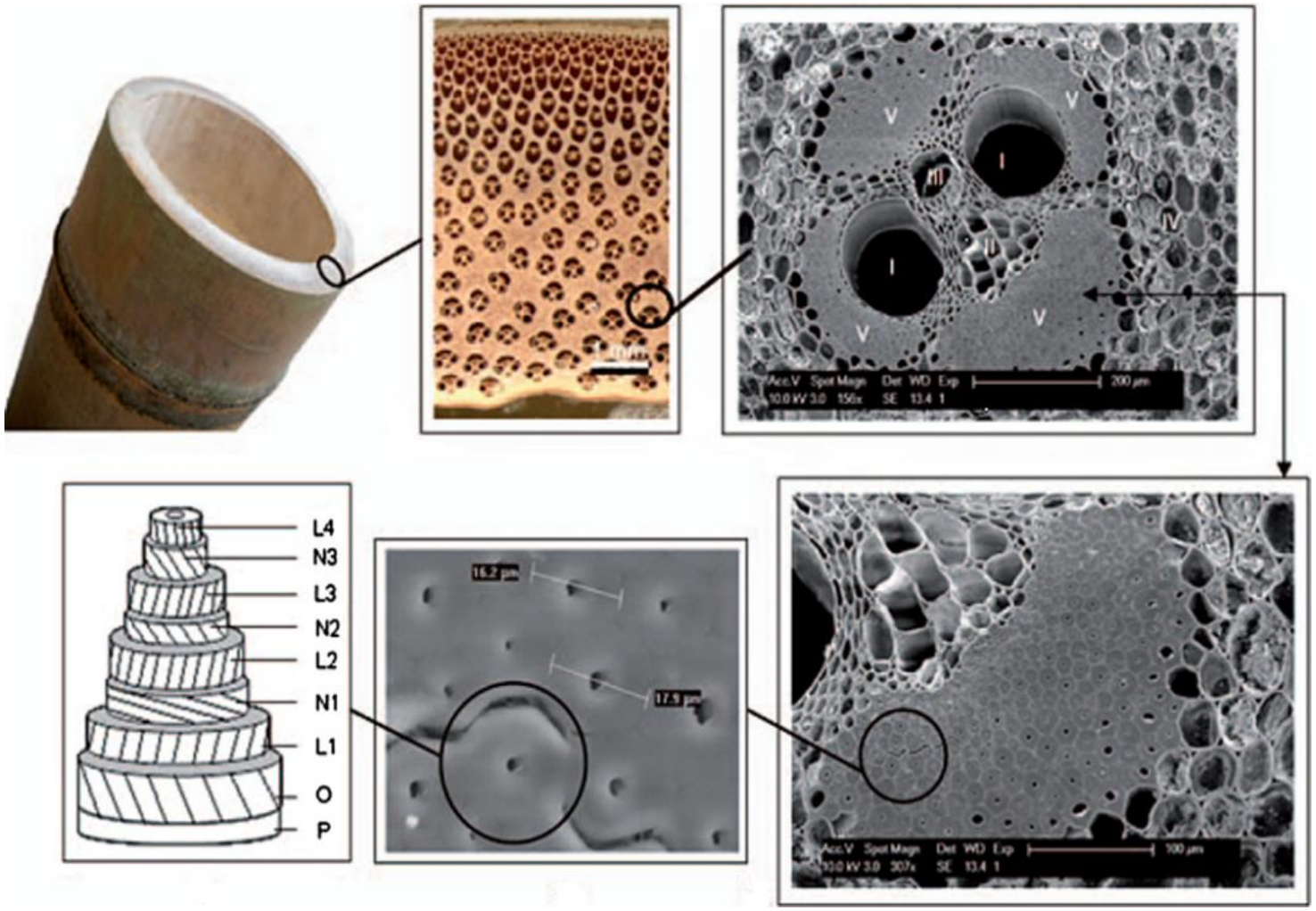
Building materials

Cellulose - composites



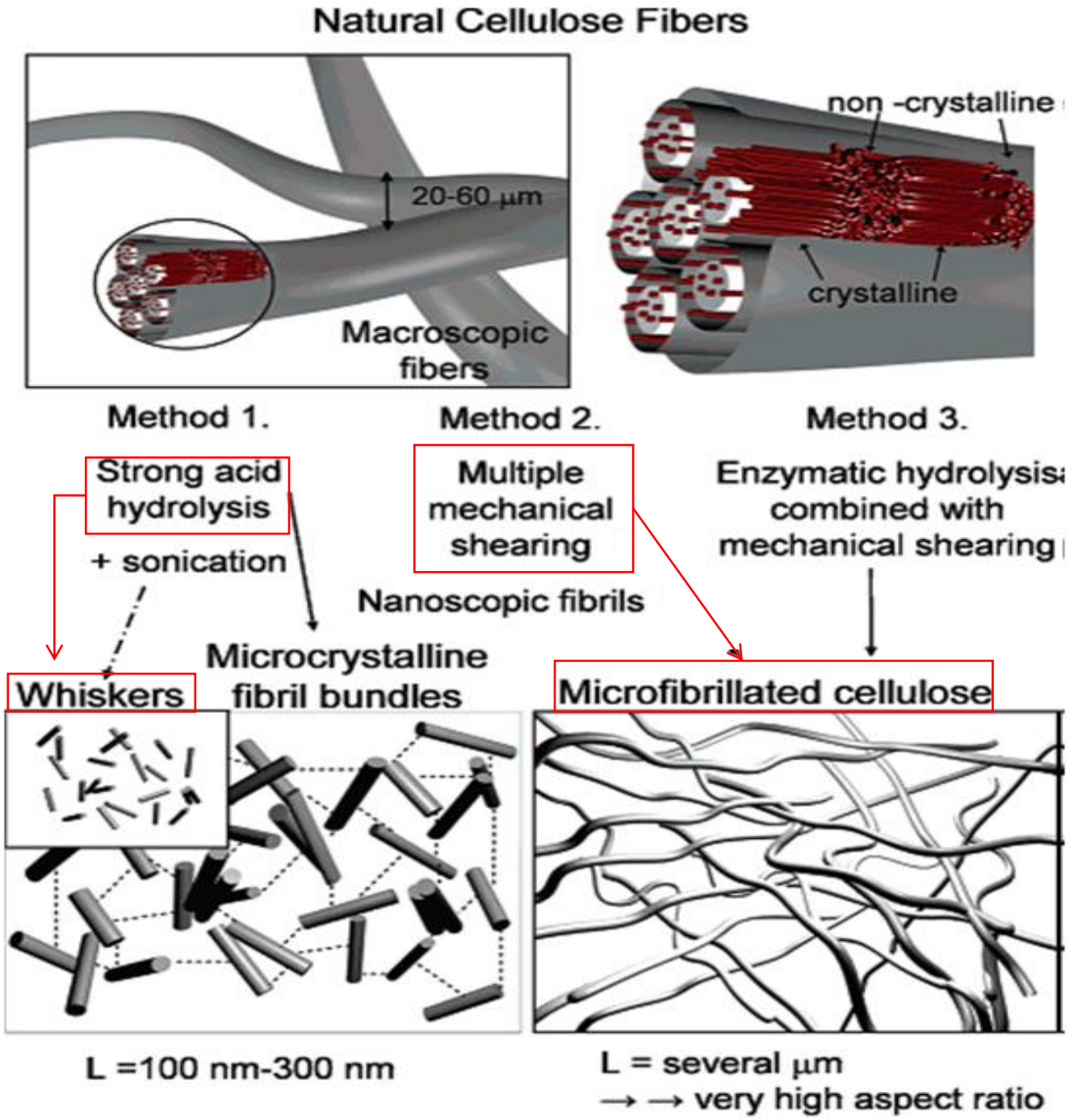
Osorio L, Trujillo E, Van Vuure A W, Verpoest I.J. Reinf Plast Compos 2011, 30: 396-408.

Nanofibrillated cellulose

- Natural and renewable resource;
- High surface area;
- High aspect ratio;
- Low weight;
- High strength and stiffness

- V – fiber bundles
- I – vessels
- Yellow area - parenchima

Nanofibrillation process



PÄÄKO, M. et al. (2007)

Chemical pulping

- Partial removal of lignin, hemicellulose and extractives
- Individualization of micro fibers

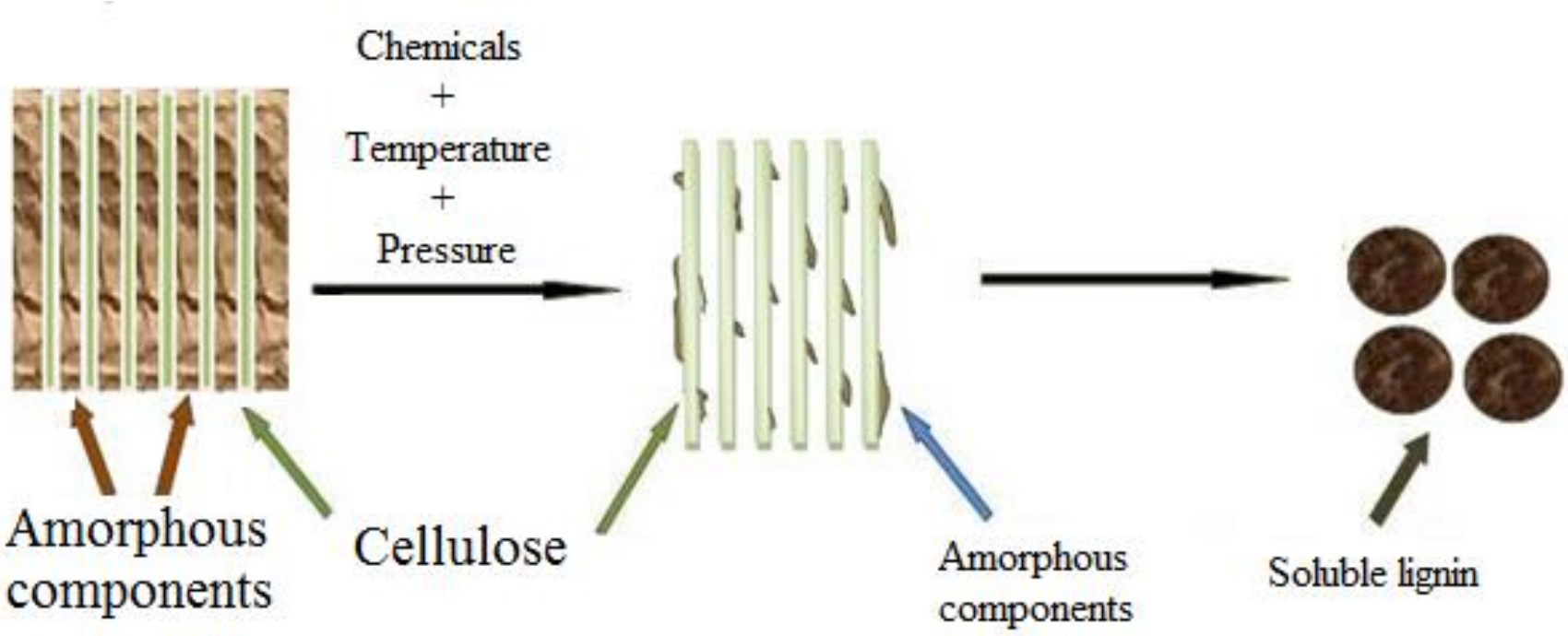
Bamboo fibers before organosolv pulping

Bamboo organosolv pulp

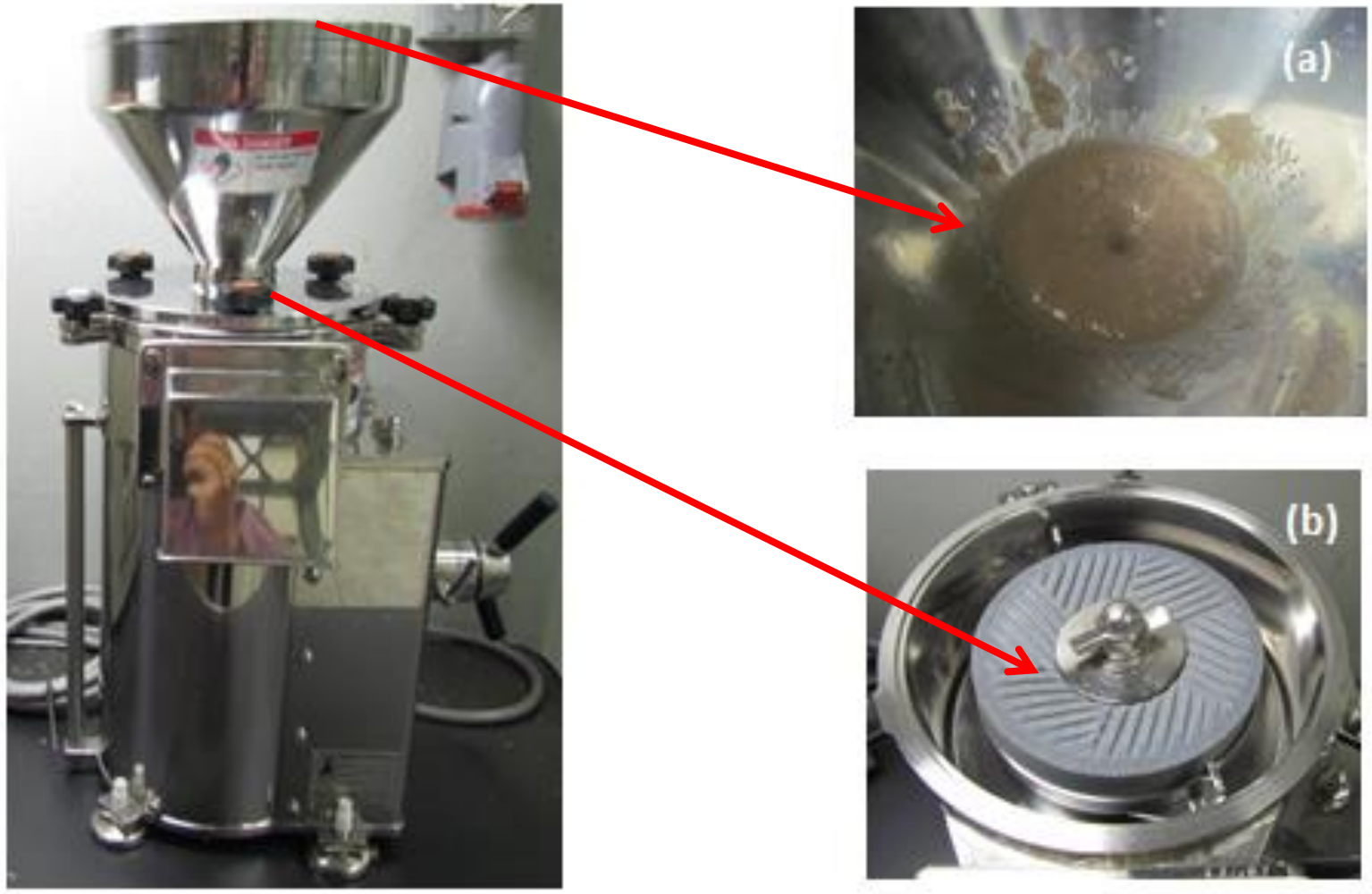
Chemical pulping

Partial removal of amorphous components of the vegetable fibers

Ex.: lignin, hemicellulose

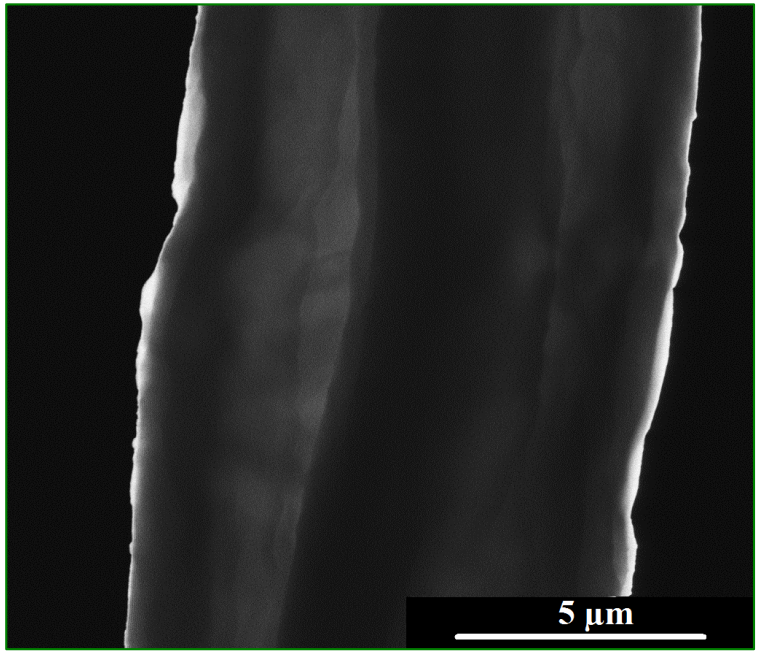


Mechanical nanofibrillation – Grinding method



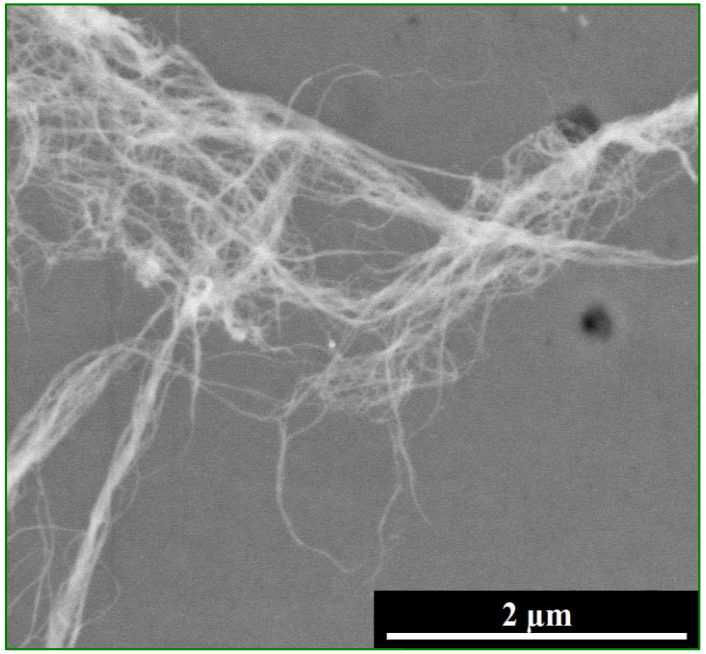
Nanofibrillated cellulose obtained by grinding

Unbleached bamboo organosolv pulp



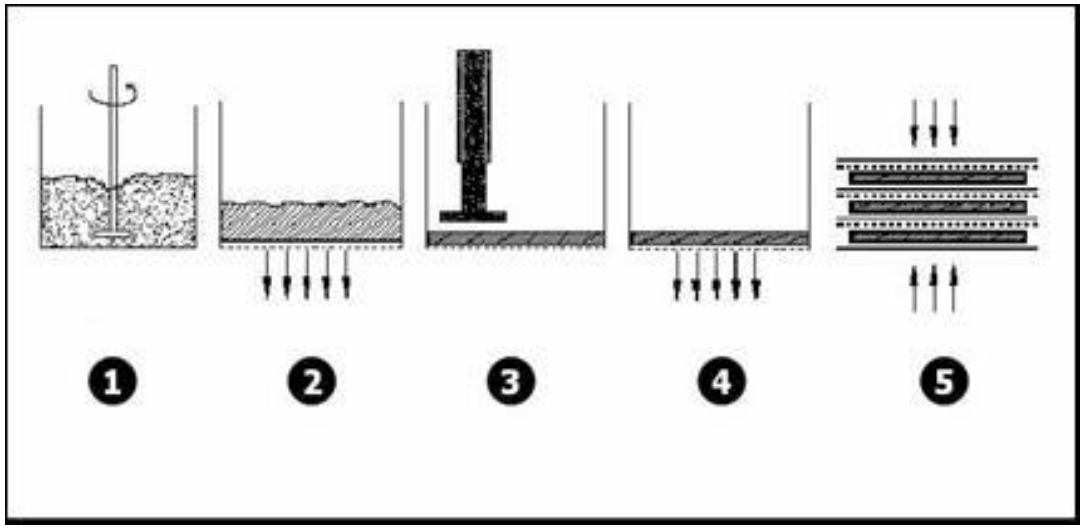
Grinding

Unbleached nanofibrillated cellulose



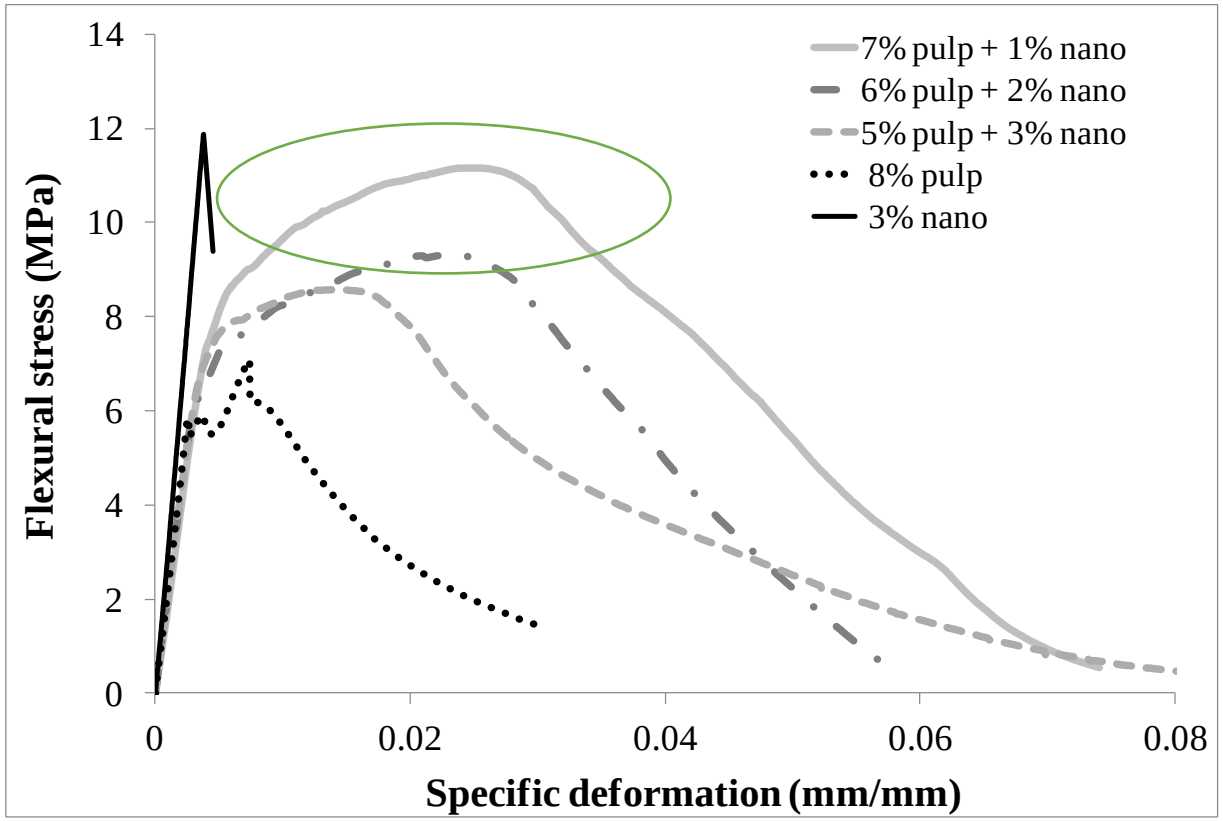
Correia et al. Grinding process for the production of nanofibrillated cellulose based on unbleached and bleached bamboo organosolv pulp. **Cellulose**, v. 23, n. 5, p. 297117, 2016.

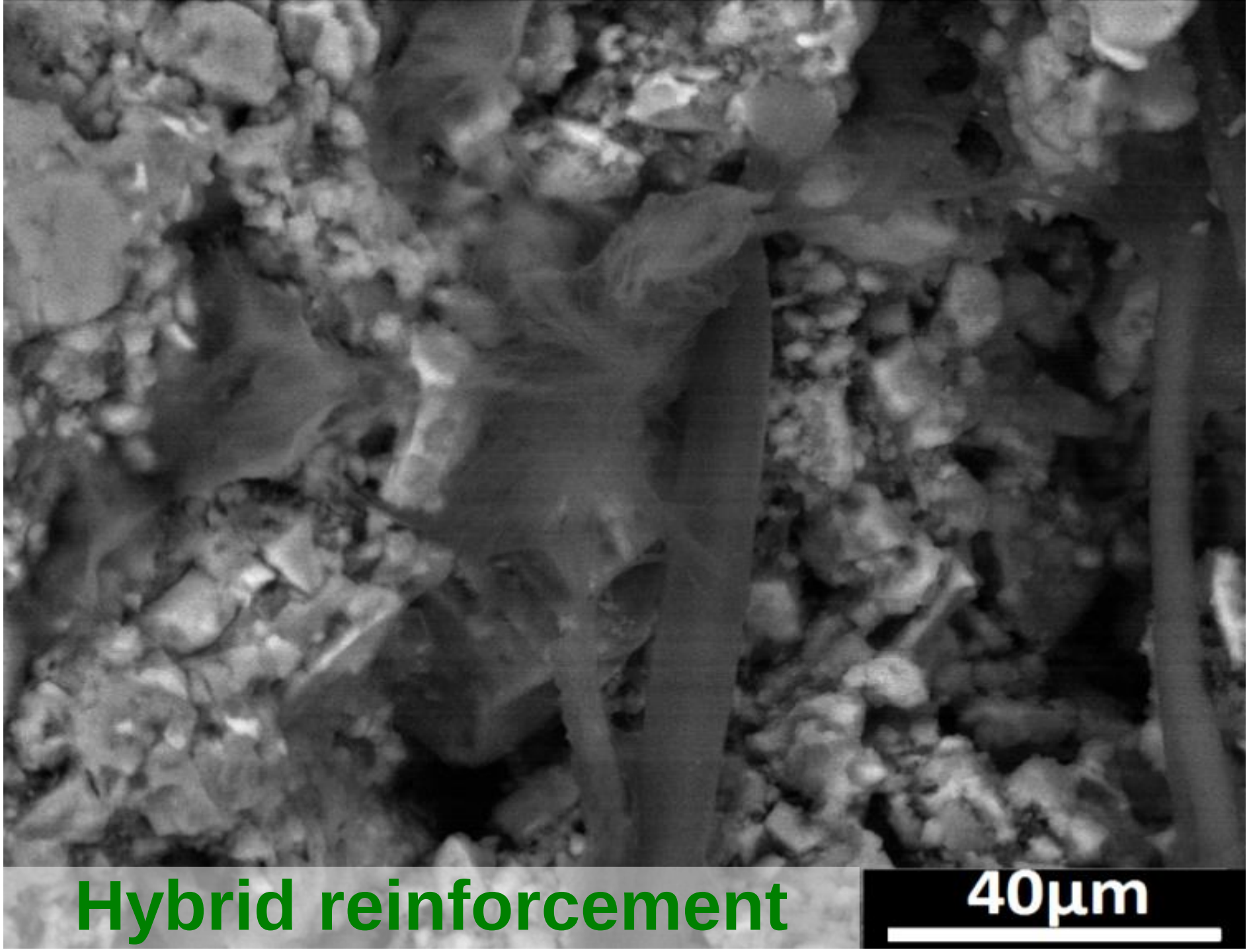
Composites Production
Slurry dewatering method



1. Mixture
2. Initial vacuum
3. Tapping pads
4. Re-application of the vacuum
5. Pressing of the plats (3.2 MPa)

Multi-scale reinforcement



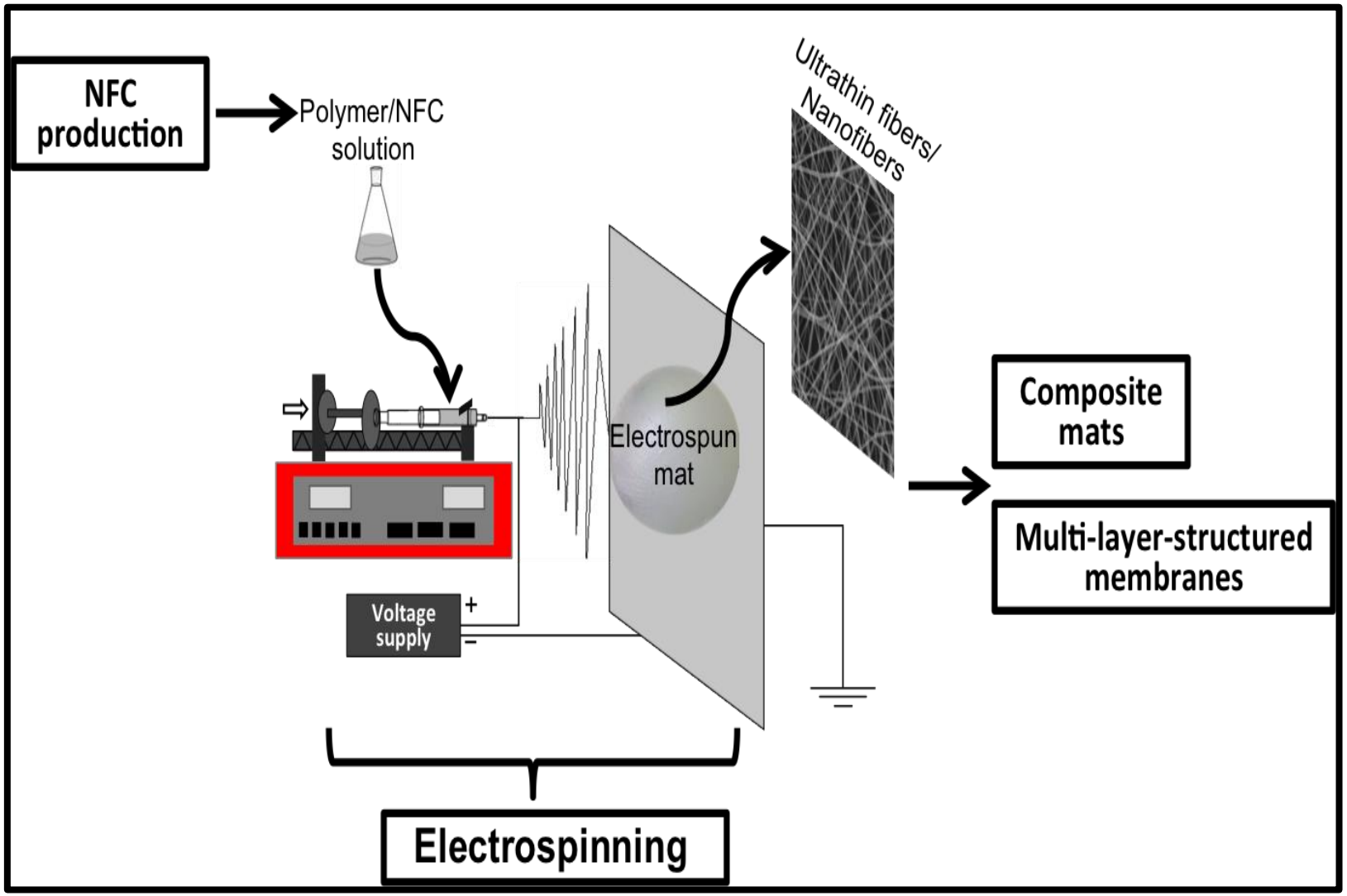

Hybrid reinforcement
40µm

Application of nanofibrillated cellulose from bamboo/sisal fibers in air filtering media

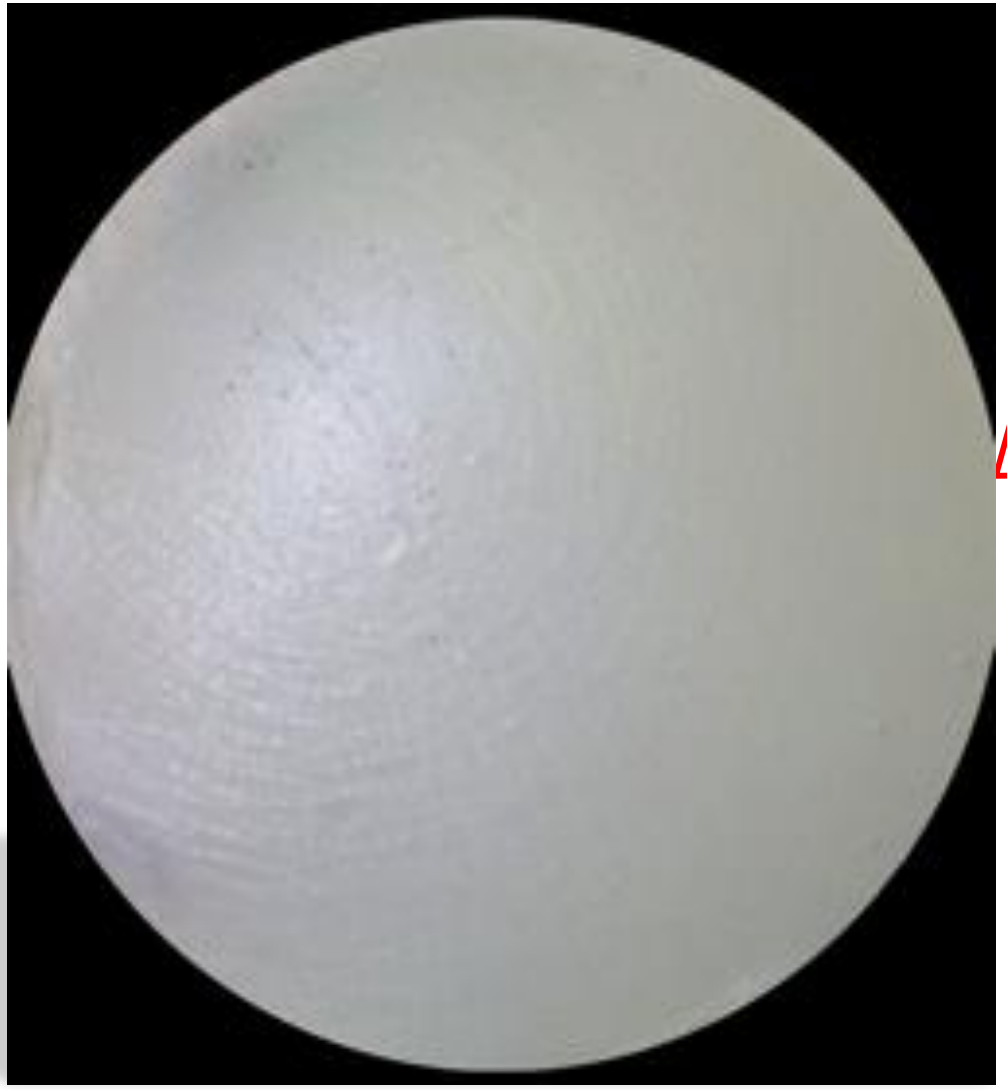
Electrospinning of solutions based on commodity polymers

- polyacrylonitrile (PAN)
- poly (ethylene terephthalate) (PET)
- polymethylmethacrylate (PMMA)

Evaluation of → NFC as reinforcing agent
→ Influence of fiber alignment



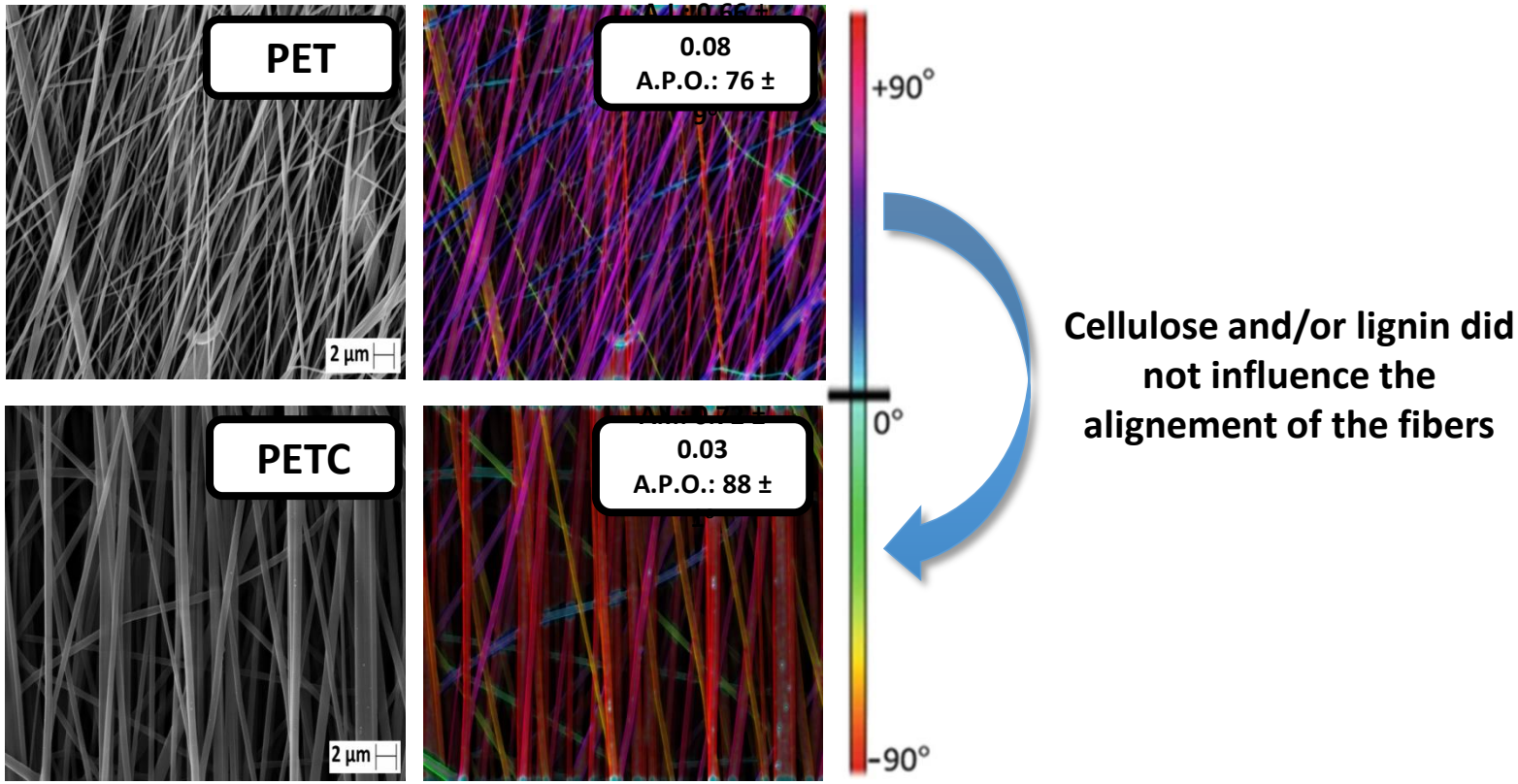
Mats of ultrathin fibers/nanofibers



- Bio-based air filtering media
- Non-toxic and non-abrasive
- Diameters at nanoscale and submicron scale
- High porosity and specific surface area
- Superior mechanical properties compared to filters based on synthetic fibers (glass fibers)

Preparation of the ultrathin fibers/nanofibers

- sisal/bamboo cellulose (C),
- lignin (L) and
- recycled PET

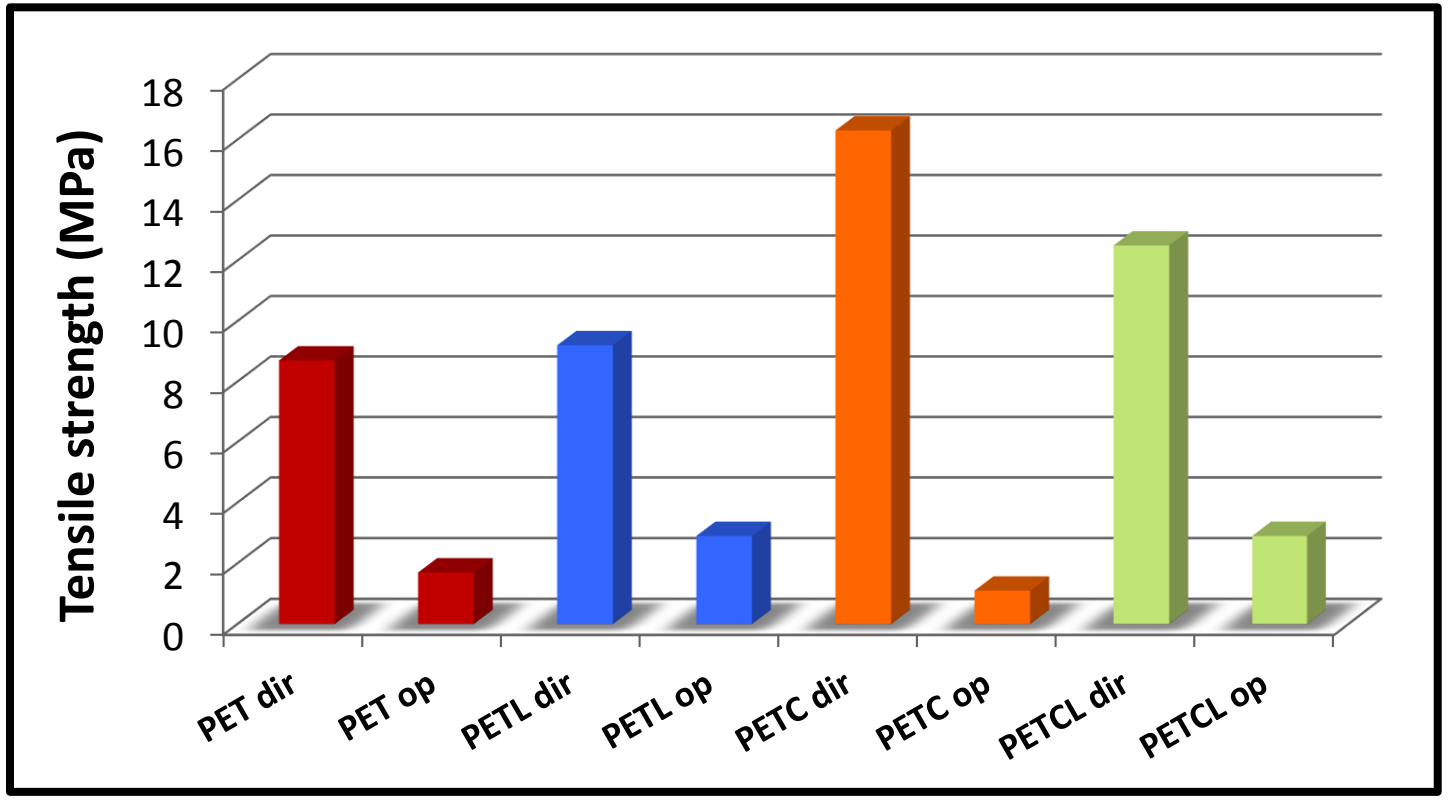


Cellulose and/or lignin did not influence the alignement of the fibers

* A.I.: Alignment index
A.P.O.: Average preferred orientation

Mats of ultrathin fibers/nanofibers, porous sheets and multi-layer-structured polymeric materials reinforced with nanofibrillated cellulose

- Previous work: Preparation of ultrathin fibers/nanofibers from sisal cellulose (C), lignin (L) and recycled PET



dir: Tensile in the direction of fiber orientation
op: Tensile in the perpendicular direction of the fiber orientation

Mechanical performance

- Bridge for transfer of stress on cracks and pores;
- Reinforcement mechanisms in nanoscale;
- Mitigation of cracking;
- Increase of modulus of elasticity and modulus of rupture

Final Remarks

- Potential and utility of characterization techniques for identifying improved behavior of cellulose fibers
  - Morphological
  - Physical
  - Mechanical
  - Chemical
- Microstructure analysis

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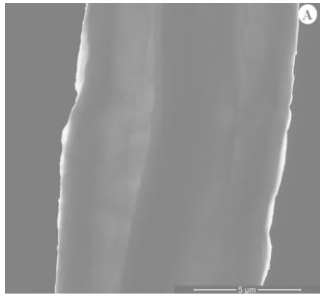

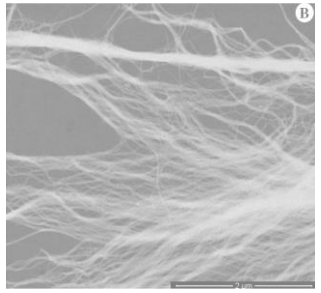

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Building materials

Full culm bamboo

Dinoderus minutus

Without treatment.....

Reasons for treatment:

- Economical aspects
- Durability
- Mechanical properties maintenance
- More applications
- Functions (Protection):
  - Biological degradation
  - Water/moisture
  - Solar radiation
  - Fire

Important for civil construction

http://www.cru-architecten.be

Full culm bamboo

Wood / Bamboo

- **Conventional chemical treatment (Brazil):**

✓ CCA
✓ CCB
✓ Creosote

Life cycle??

✓ Boron compounds
✓ Copper Sulphate
✓ Others

Mostly used for Bamboo
However:
- Leaching problem
- Lack of assessment

Assessment

Alternatives:

✓ Pirolenous acid
✓ Heat treatment
✓ Furfurilic alcohol
✓ Tannin

In-situ polymerization

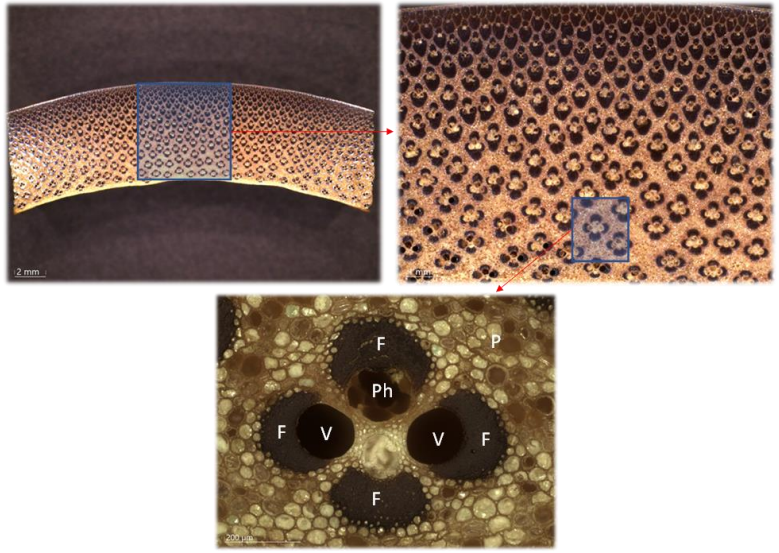
✓ Acetic anhydride
✓ Citric acid

Chemical modification

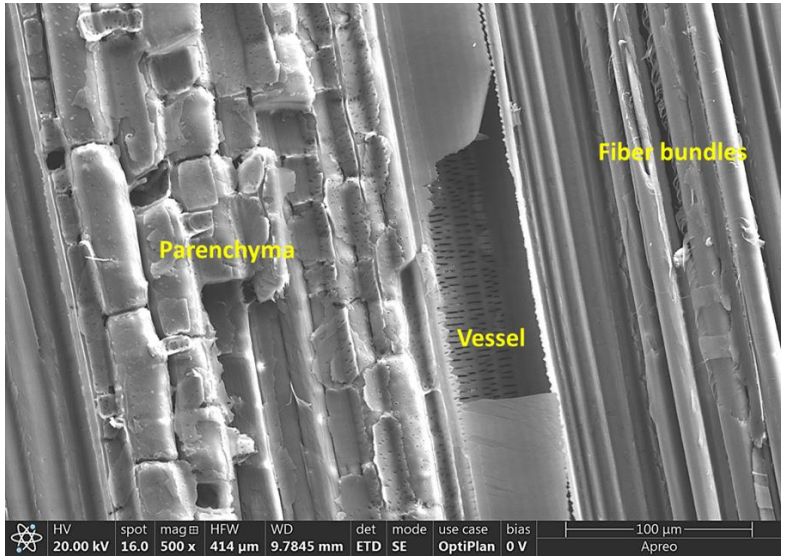
Development

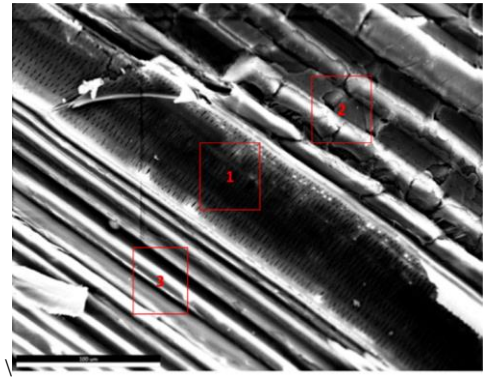
Conventional treatment assessment (CCB)

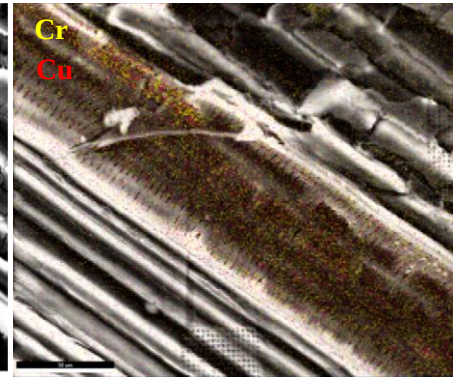
Microstructural and chemical characterization
→ Quality control



V= Vessels, F= Fiber bundles, Ph= Phloem, P= Parenchyma







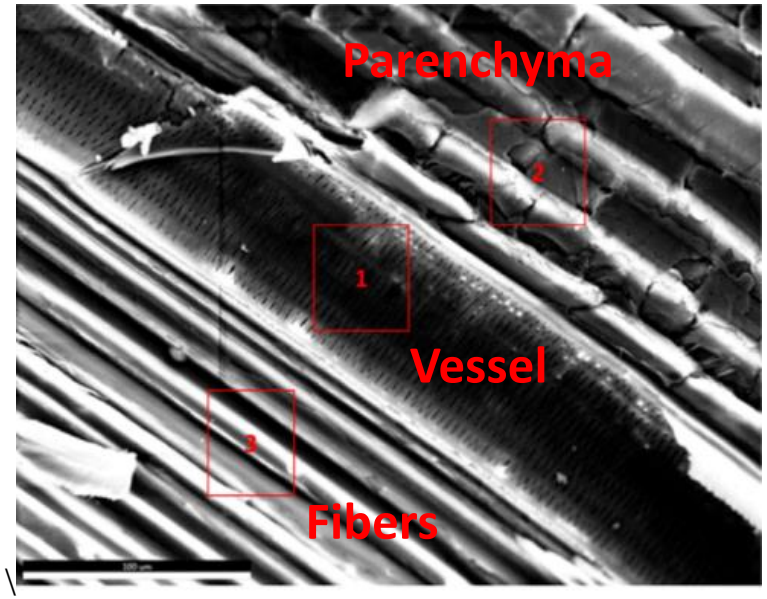
Element	Entire area		1		2		3	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C K	55.25	63.53	45.26	64.8	60.79	67.85	60.97	67.65
O K	41.29	35.64	24.41	26.24	38	31.84	38.76	32.28
Cr K	1.56	0.41	12.47	4.13	1.22	0.31	0.15	0.04
Cu K	1.89	0.41	17.86	4.83	-	-	0.12	0.03

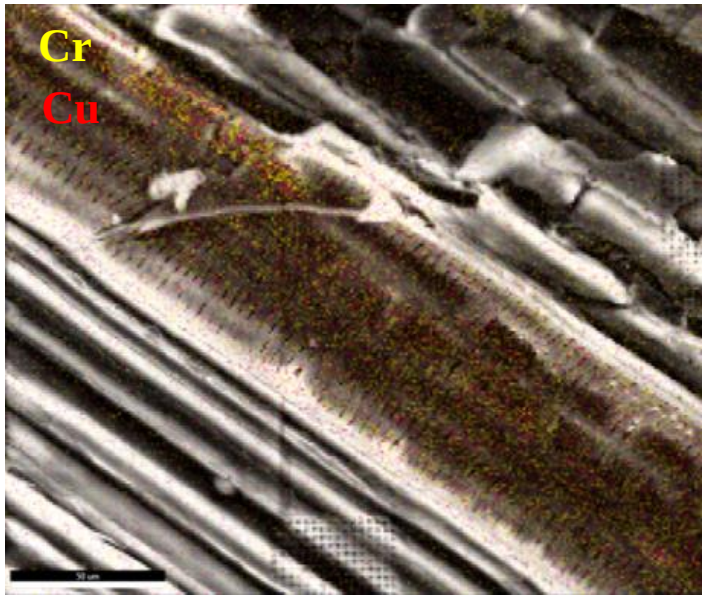
Concentration of chemicals (Cr and Cu) in the vessels, although satisfied retention achieved.

Conventional treatment assessment

Tracking chemicals in the bamboo microstructure

CCB treated using full-cell process – Retention ≈ 6.5 kg/m^3





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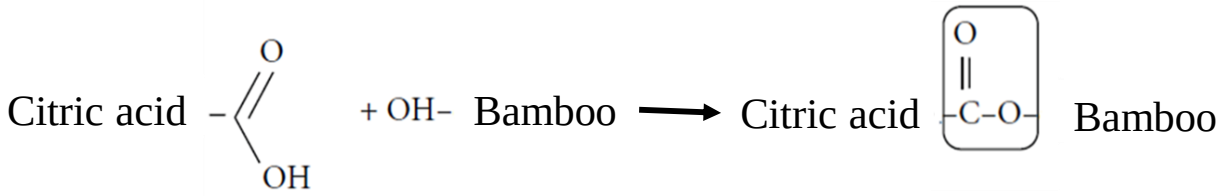
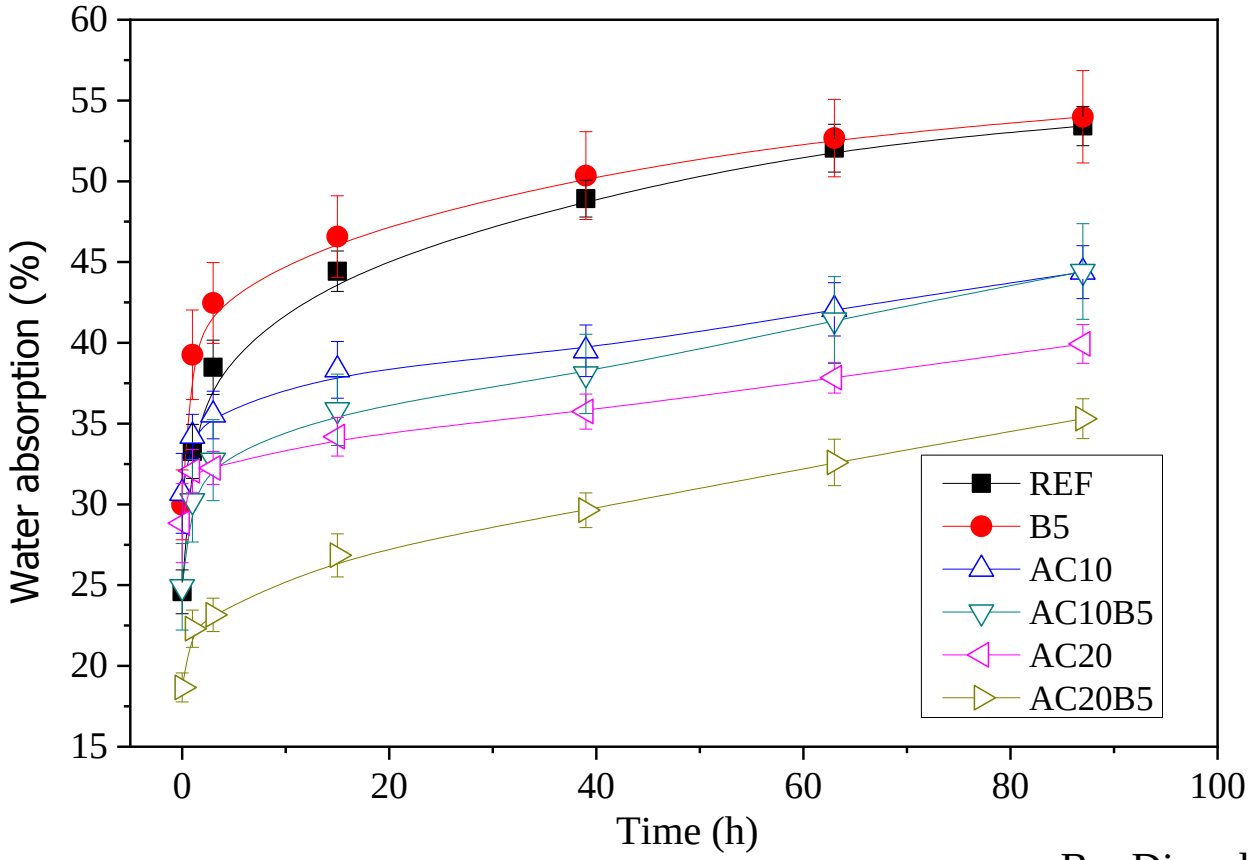
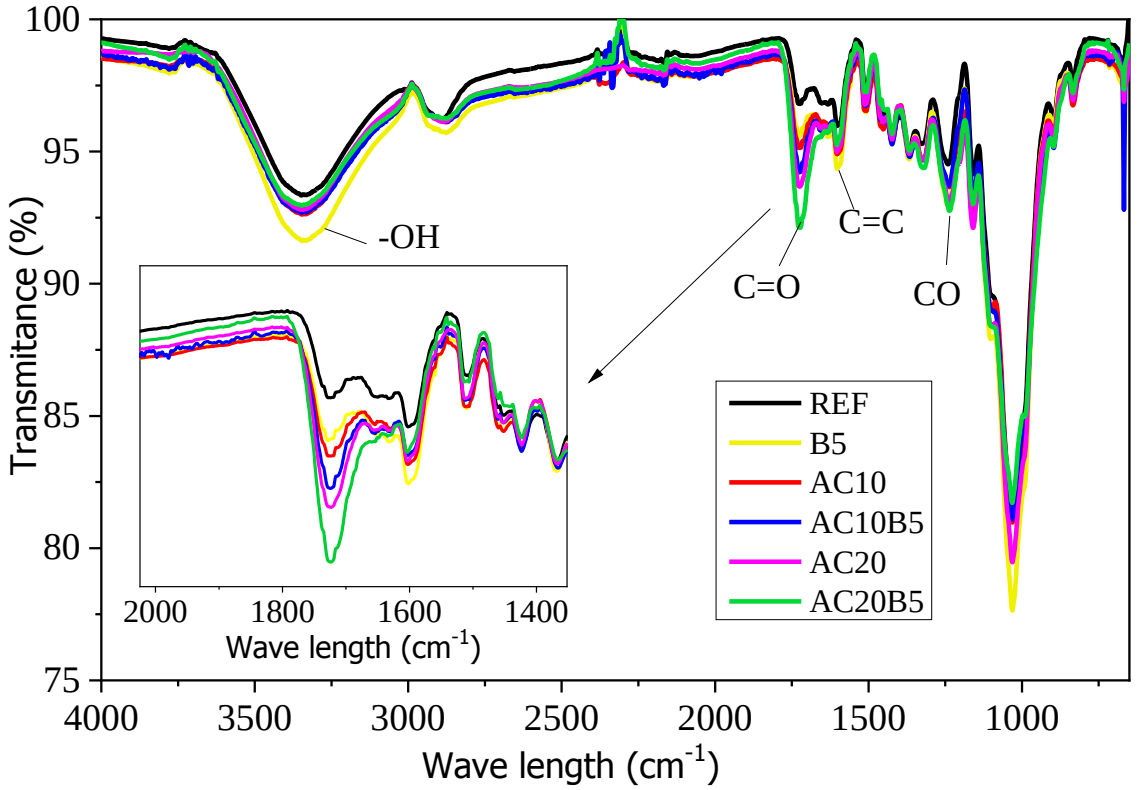
Chemical modification - Alternatives

Increase dimensional stability and decrease water absorption through esterification process





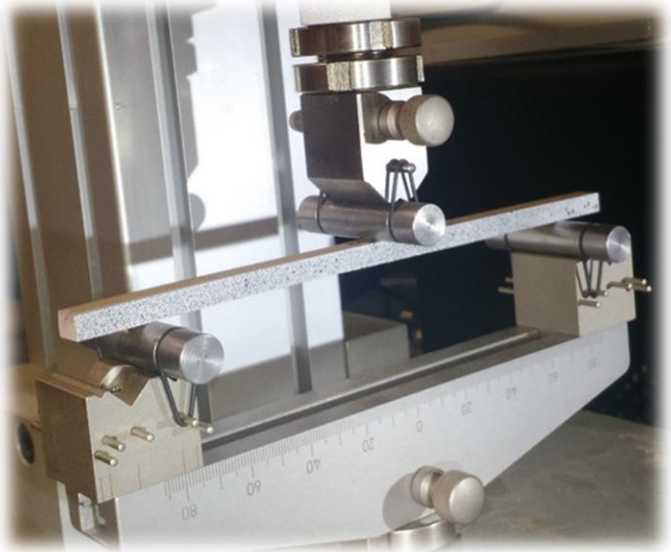


B – Dissodium octaborate tetrahydrate (DOT)
AC – Citric acid
ACB – Citric acid + DOT

Quality control:
Mechanical characterization

Improving bamboo testing methods

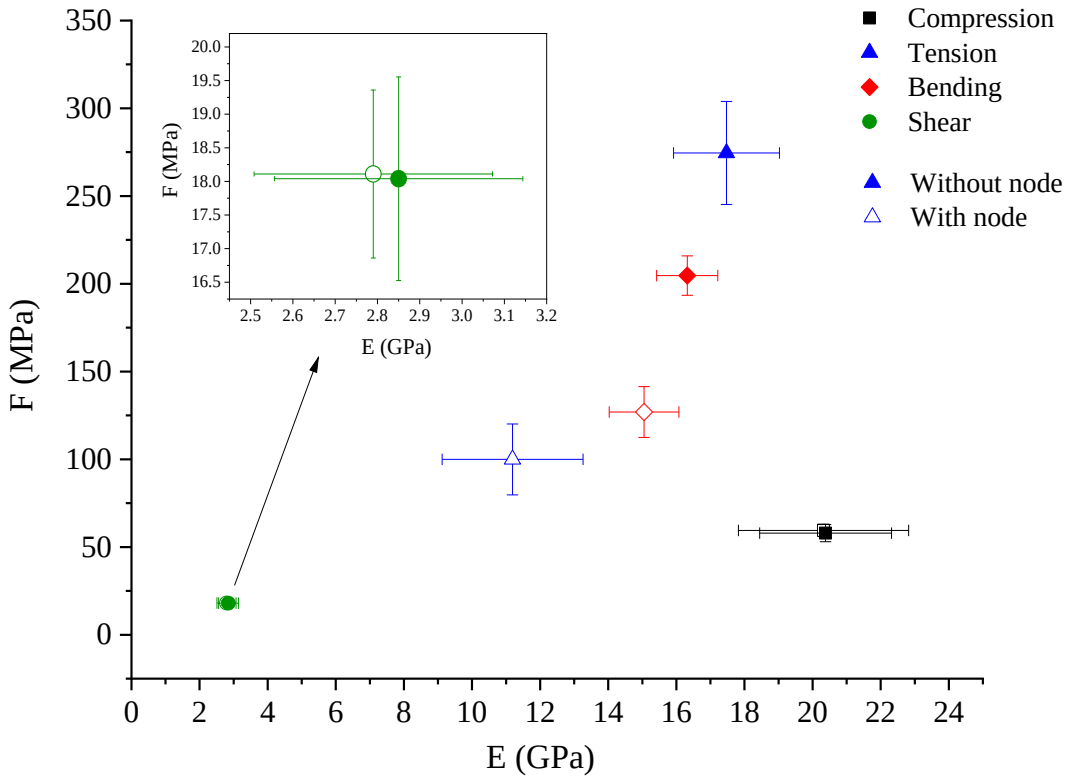
Mechanical Test	Standard /Guidelines
Compression // Fibers	ISO 22157
Shear // Fibers	ISO 22157
Flat ring flexure	(IRGO et al., 2017)
Three-point bending	ASTM D143-14 /ASTM D7264
Tensile // Fibers	ISO 22157 (with modification)



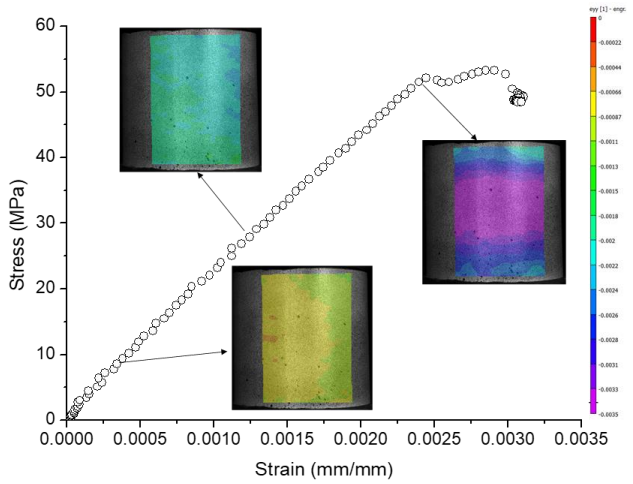
PITT | SWANSON ENGINEERING

Digital image correlation

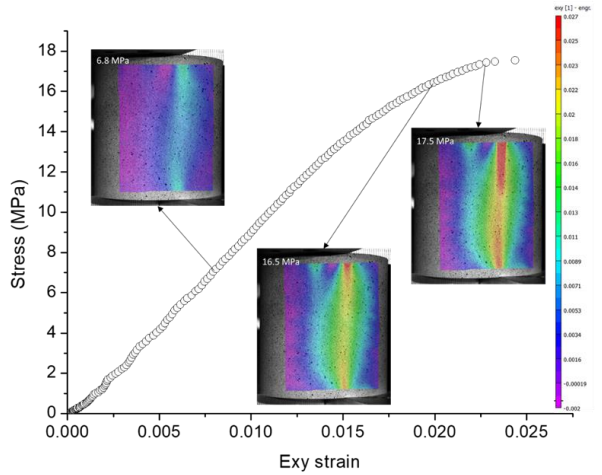
Strain distribution in different loading conditions



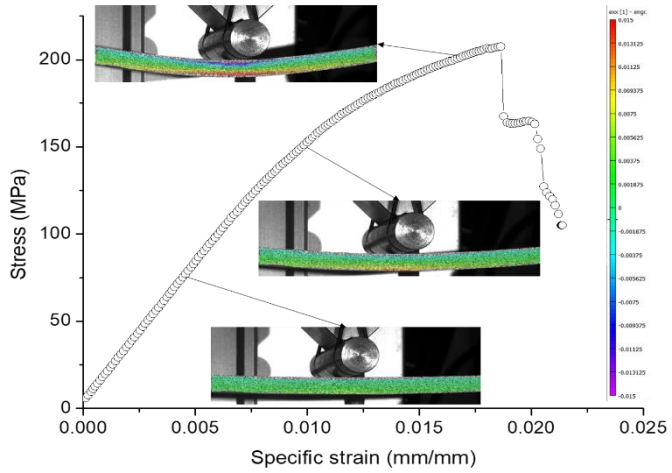
Compression



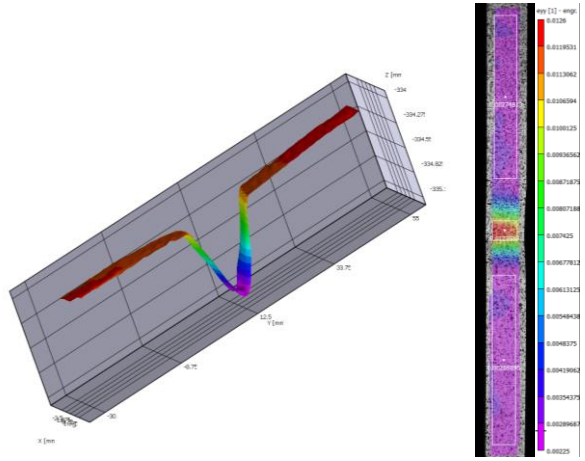
Shear



Bending



Tension



Validation of bamboo mechanical characterization standard → additional mechanical properties

Full characterization – Phyllostachys edulis bamboo (Moso)

Complete mechanical characterization and influence of chemical treatment:
A → CCB (external applications)
B → Dissodium octaborate tetrahydrate (protected environments)

No difference between treatment methods

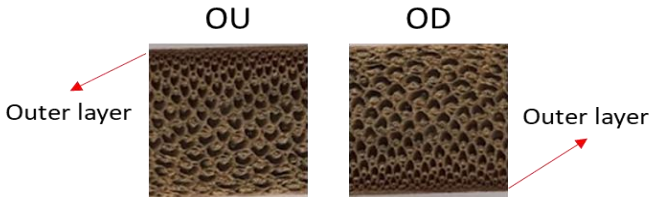
Condition		Average density (g cm^{-3})	Three-point bending					Tensile // fibers				
			N	MOR (MPa)		MOE (MPa)		N	$F_{T,0}$ (MPa)		$E_{T,0}$ (MPa)	
				AVR	COV	AVR	COV		AVR	COV	AVR	COV
Internode	A	0.80	18	203.20	0.028	16.21	0.034	18	292.14	0.064	18.42	0.045
	B	0.80	18	208.51	0.055	16.55	0.053	19	283.42	0.069	18.31	0.038
	C	0.79	18	202.32	0.071	16.21	0.072	20	247.05	0.083	15.83	0.080
	All	0.80	**54**	**204.68**	**0.055**	**16.32**	**0.055**	**57**	**274.56**	**0.107**	**17.47**	**0.089**
Node	All		**24**	**126.93**	**0.114**	**15.05**	**0.068**	**27**	**99.94**	**0.202**	**11.19**	**0.185**

Condition		Average density (g cm^{-3})	Compression // fiber					Shear // fiber					Flat Ring Flexure		
			N	$F_{c,0}$ (MPa)		$E_{c,0}$ (GPa)		N	F_v (MPa)		Shear Modulus (GPa)		N	F_r (MPa)	
				AVR	COV	AVR	COV		AVR	COV	AVR	COV		AVR	COV
Internode	A	0.80	16	58.11*	0.074	21.82	0.059	15	18.14*	0.060	2.97	0.058	8	13.29	0.212
	B	0.80	15	54.89*	0.064	21.73	0.067	9	19.62*	0.052	2.99	0.097	7	13.31	0.104
	C	0.79	24	59.80*	0.096	19.07	50.91	25	17.46*	0.077	2.71	0.098	13	10.69	0.269
	All	0.80	**41**	**57.93**	**0.084**	**20.38**	**0.095**	**36**	**18.04**	**0.084**	**2.85**	**0.103**	**28**	**12.09**	**0.233**
Node	All		**14**	**59.51**	**0.059**	**20.32**	**0.123**	**13**	**18.11**	**0.069**	**2.79**	**0.101**		-	-

Digital image correlation

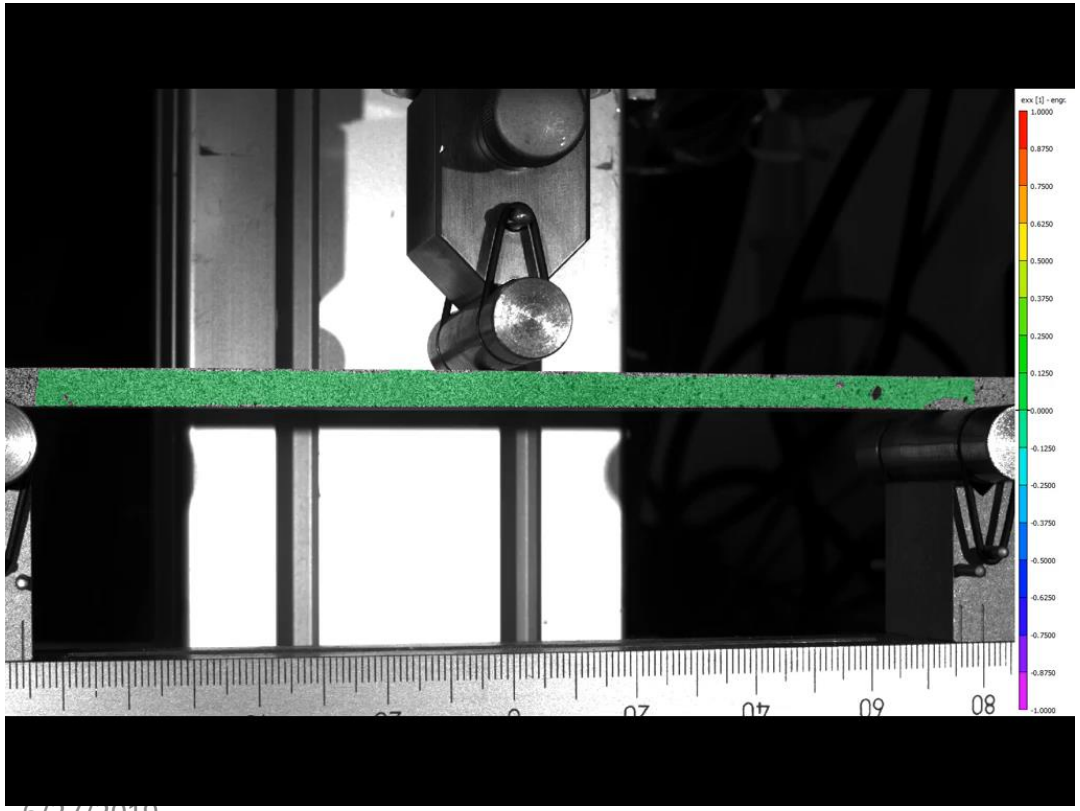
Influence of the different fiber distribution / orientation

Data for modelling



Condition	N Samples	ρ (g/cm³)		Moisture content (%)		MOR (MPa)		MOE (GPa)	
		AVR	COV	AVR	COV	AVR	COV	AVR	COV
OD	10	0.787	0.048	7.39	0.112	**182.8**	**0.084**	15.6	0.078
OU	54	0.790	0.039	7.33	0.088	**204.7**	**0.055**	16.3	0.055

Condition	N Samples	Specific MOR (MPa)		LOP (MPa)		SE (kJ/m²)		Specific strain at MOR (mm/mm)	
		AVR	COV	AVR	COV	AVR	COV	AVR	COV
OD	10	232.2	0.064	67.0	0.153	**78.5**	**0.229**	0.0318	0.152
OU	54	259.4	0.056	124.3	0.063	**39.5**	**0.133**	0.0173	0.076



Strain behavior / MOE across bamboo thickness → Understanding of the functionally graded properties

Bamboo research – BioSMat Group

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- Physical/mechanical prop.
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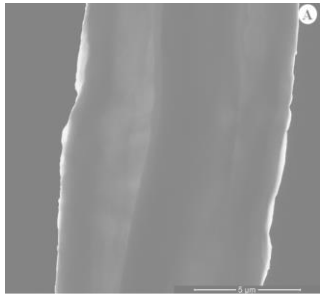
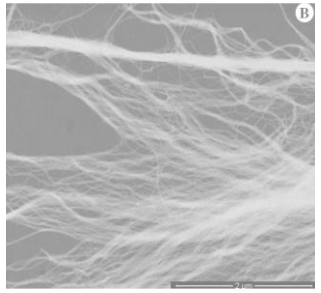
- ✓ Filters





Natural form

Bamboo poles

- ✓ Structural use
- ✓ Preservative treatment
- ✓ Standardization

Particles / Strands / Strips

Engineered bamboo

- ✓ Particleboards
- ✓ OSB
- ✓ Densified bamboo

Building materials

Bamboo OSB

Formaldehyde-free

D. Asper (local material)

Harvested inside the university campus

Mattress of particles

ressing

Strands of Bamboo

Castor oil polyurethane resin

OSB panels

Resin produced 20 km from the University

Influence of resin content
PU (castor oil based PU)

Physical Characterization

Treatment	Water Absorption 24 h (%)	Thickness swelling 24 h (%)
650 kg/m³ 8% resin content (CV)	49,07 (10,66)	20,43 (12,49)
650 kg/m³ 10% resin content (CV)	28,81 (6,45)	13 (16,73)
650 kg/m³ 12% resin content (CV)	28,94 (6,55)	9,70 (14,22)
650 kg/m³ 15% resin content (CV)	23,51 (8,75)	8,45 (17,9)
EN 300: 2002	-	25

Bamboo OSB

Formaldehyde-free

Mechanical Caracterization

Treatment	Modulus of Rupture Long. (MPa)	Modulus of Rupture Transv. (MPa)	Modulus of elasticity Long. (MPa)	Modulus of elasticity Transv. (MPa)
650 kg/m³ 8% resin content (CV)	27,73 (19,54)	25,47 (13,19)	5804 (19,16)	2121 (11,22)
650 kg/m³ 10% resin content (CV)	40,09 (13,54)	30,37 (17,43)	6955 (18,91)	2643 (14,35)
650 kg/m³ 12% resin content (CV)	49,75 (9,76)	30,85 (17,8)	8393 (13,36)	2302 (19,23)
650 kg/m³ 15% resin content (CV)	42,63 (17,16)	25,33 (24,51)	6579 (14,96)	1845 (19,43)
EN 300: 2002 Panels OSB type 1	20	10	2500	1200

Even with 8% resin → enough for OSB type 1 requirements (EN 300:2002)

Densification process

Material performance improvement

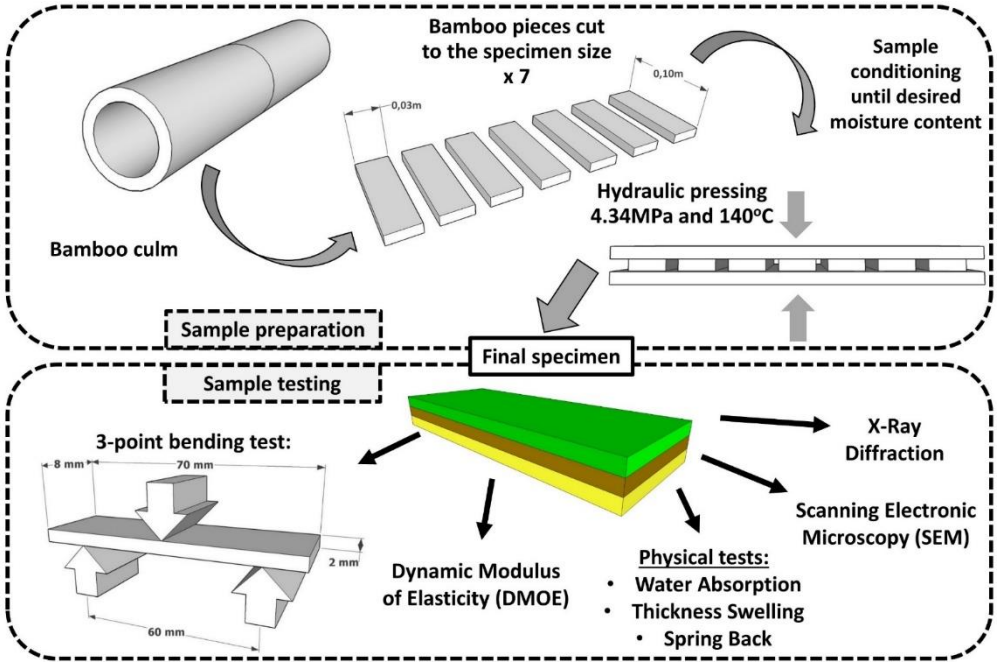
Study of the densification process

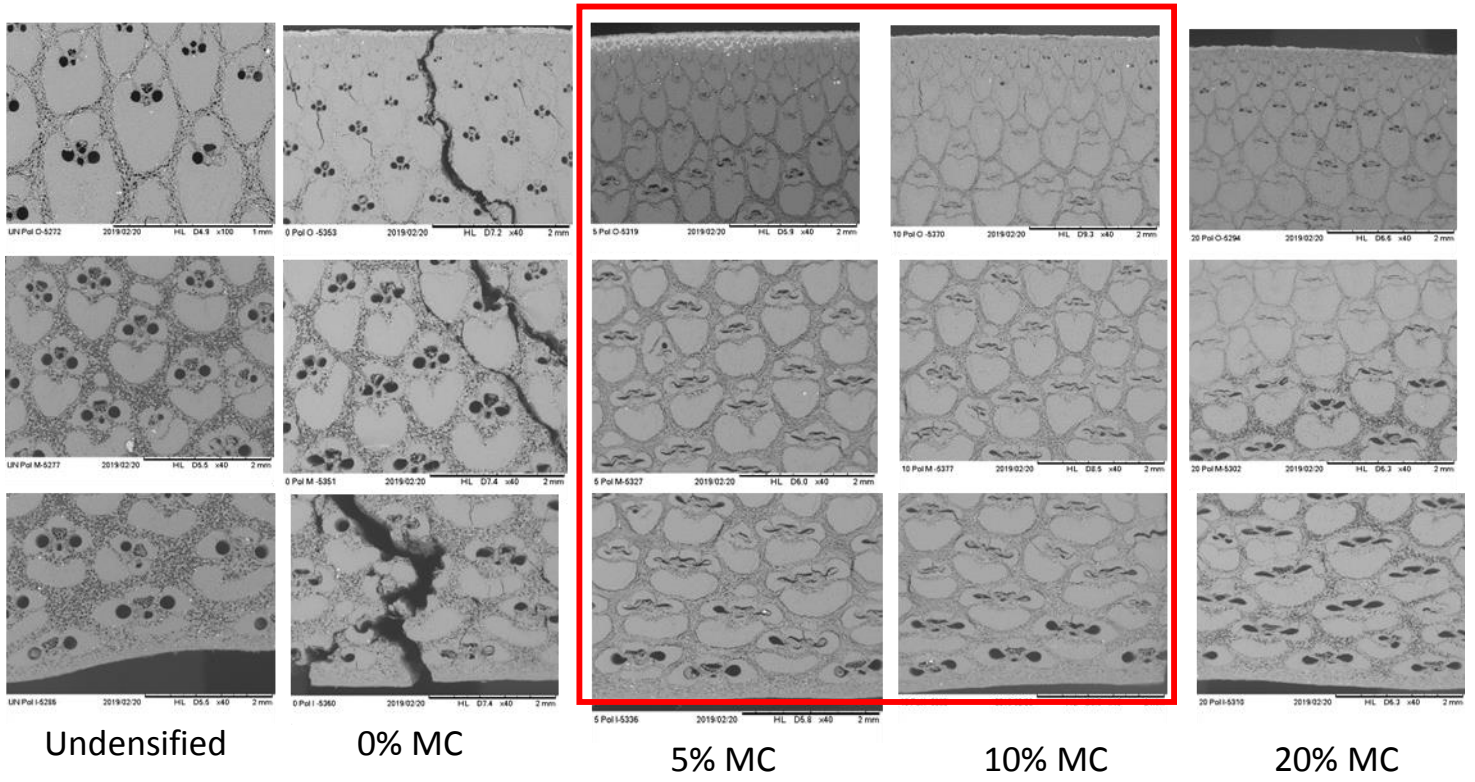
↓

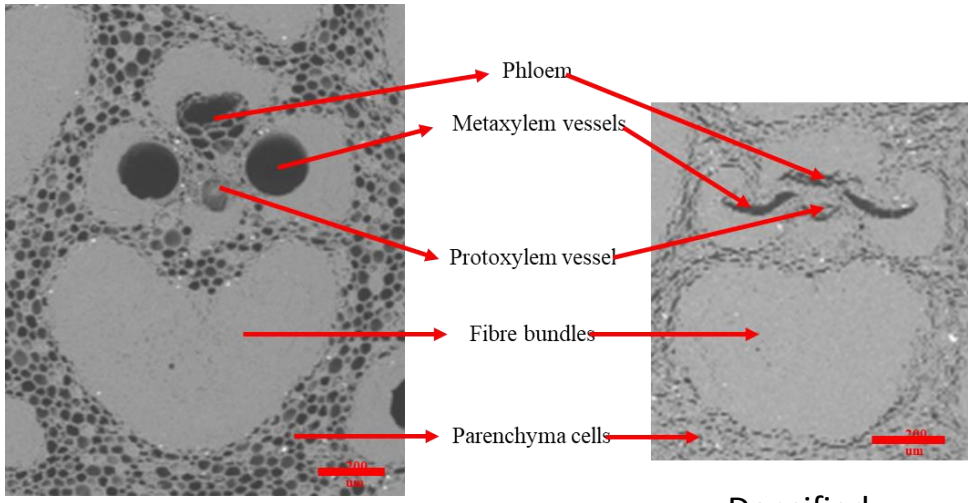
Pressure + Temperature → Above lignin Tg

↓

Influence of initial moisture content (MC)





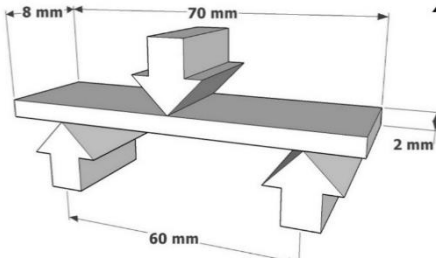


Densification process

Material performance improvement

Dendrocalamus asper bamboo

3-point bending test:

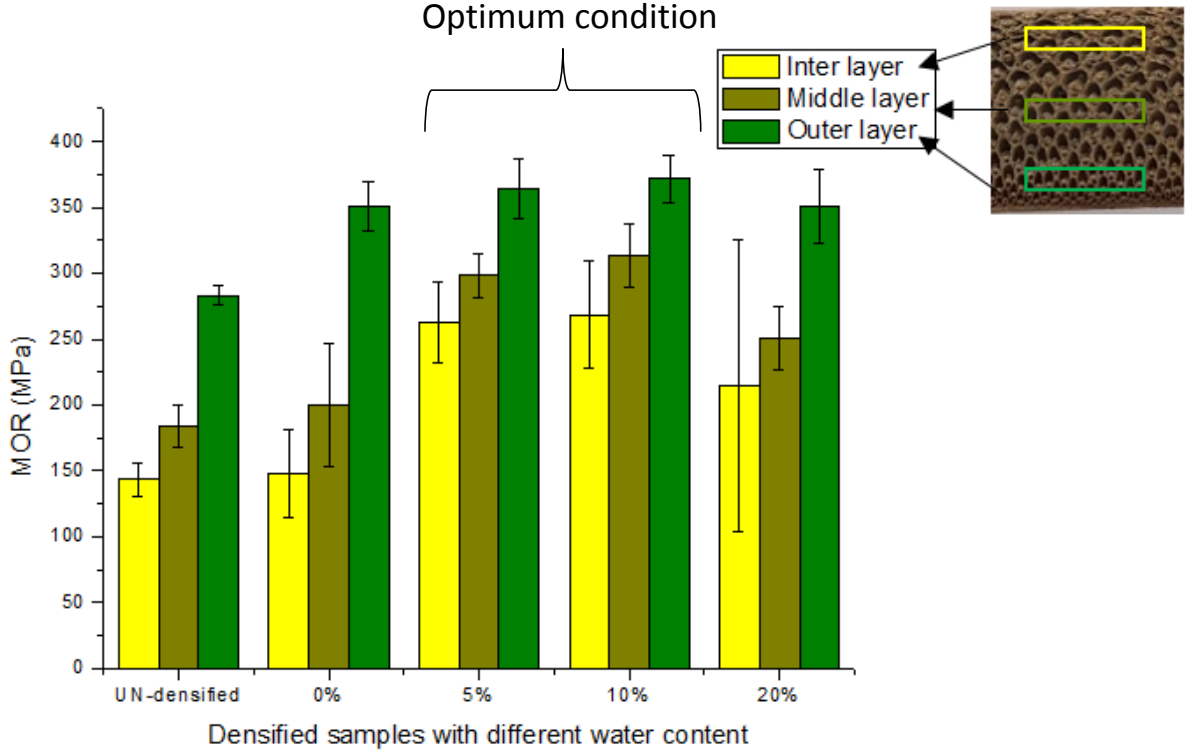


Apparent density:

Undensified: 0.6-0.7 g.cm^{-3}

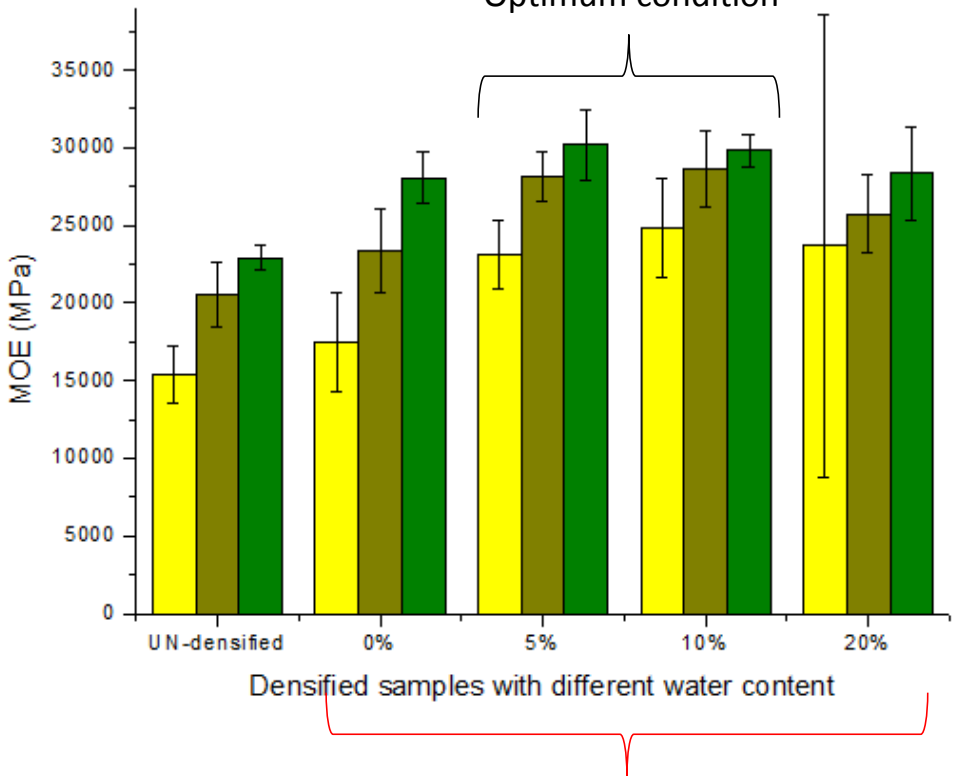
Densified: 1.0-1.2 g.cm^{-3}

Optimum condition



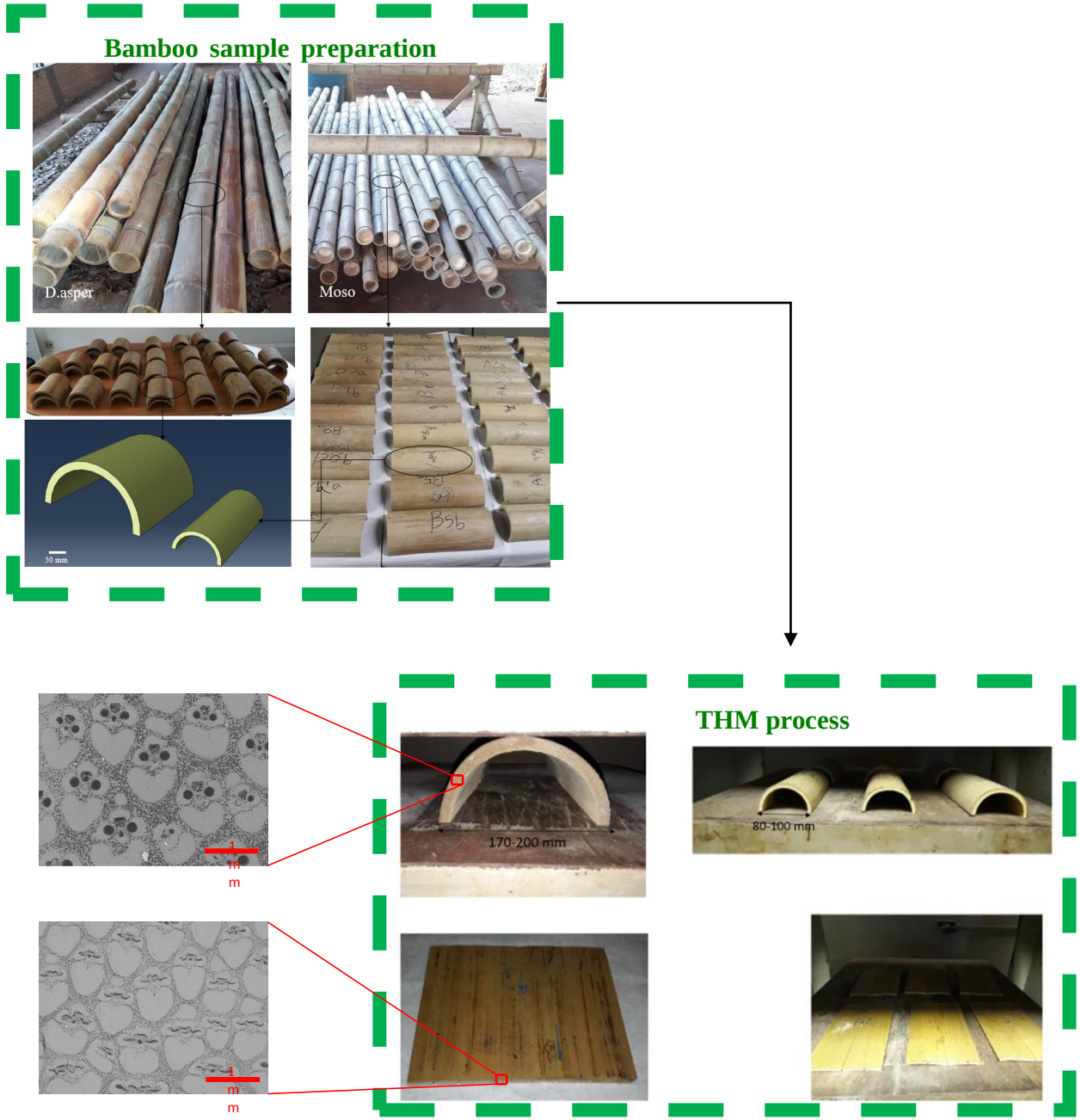
Densified samples

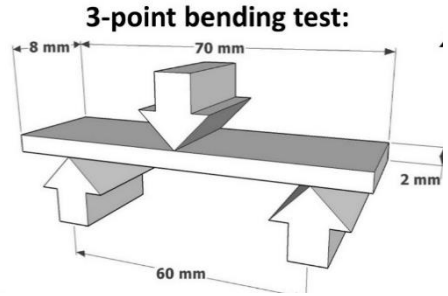
Optimum condition

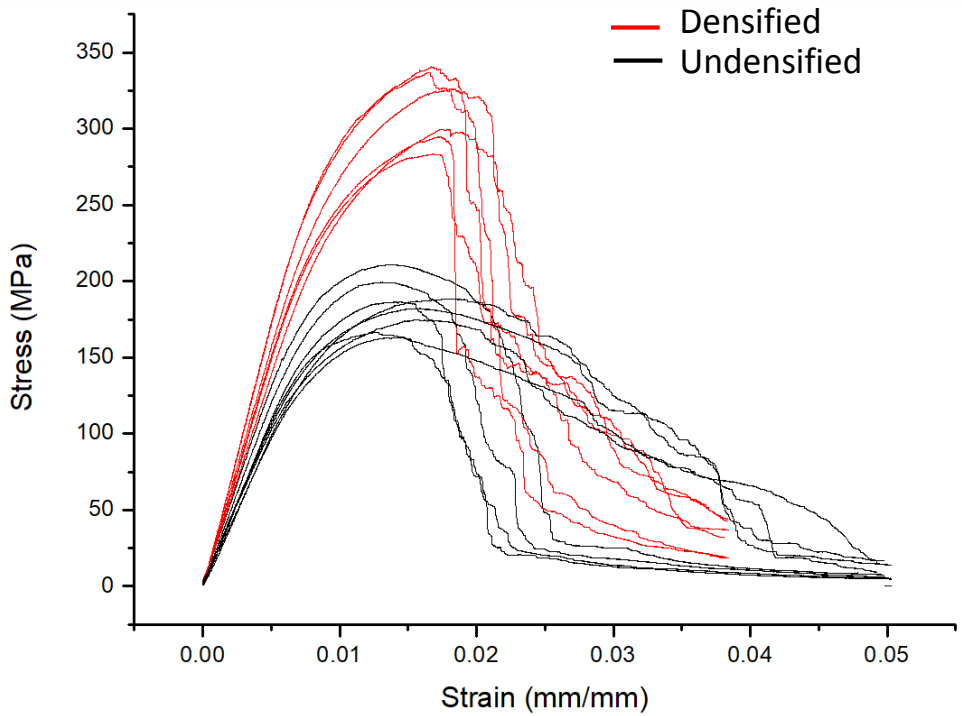


Densified samples

Flattening + densification







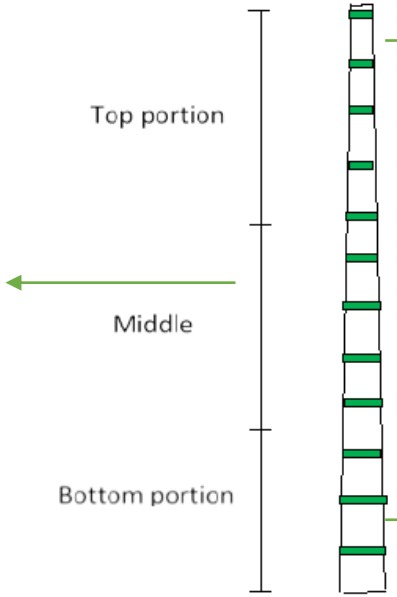
Engineered bamboo

Densified bamboo based panel

Maximum utilization ratio products

Improve performance

Flattened Bamboo



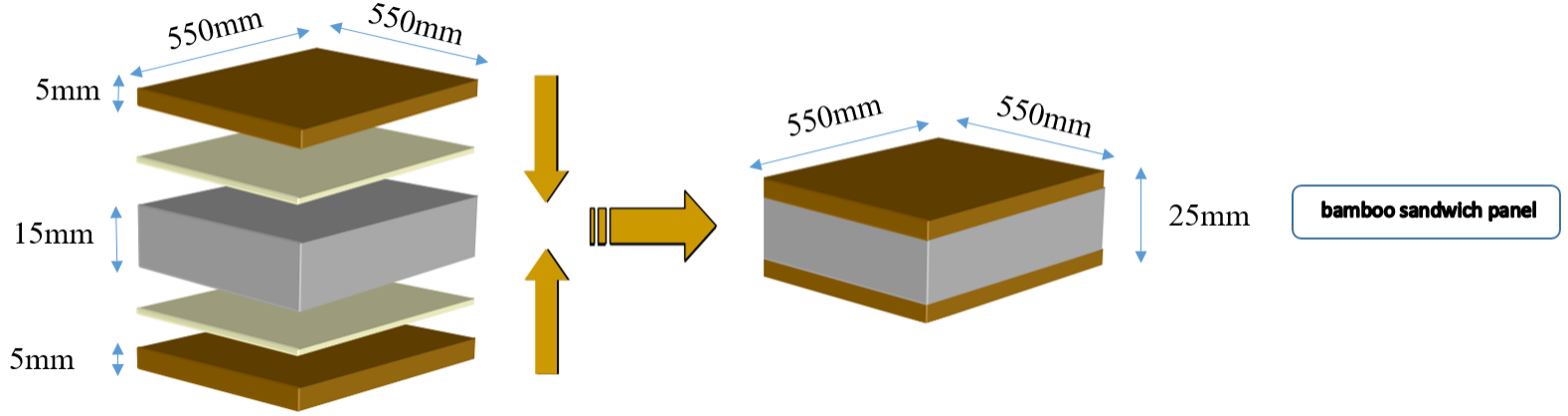
Bamboo particleboard

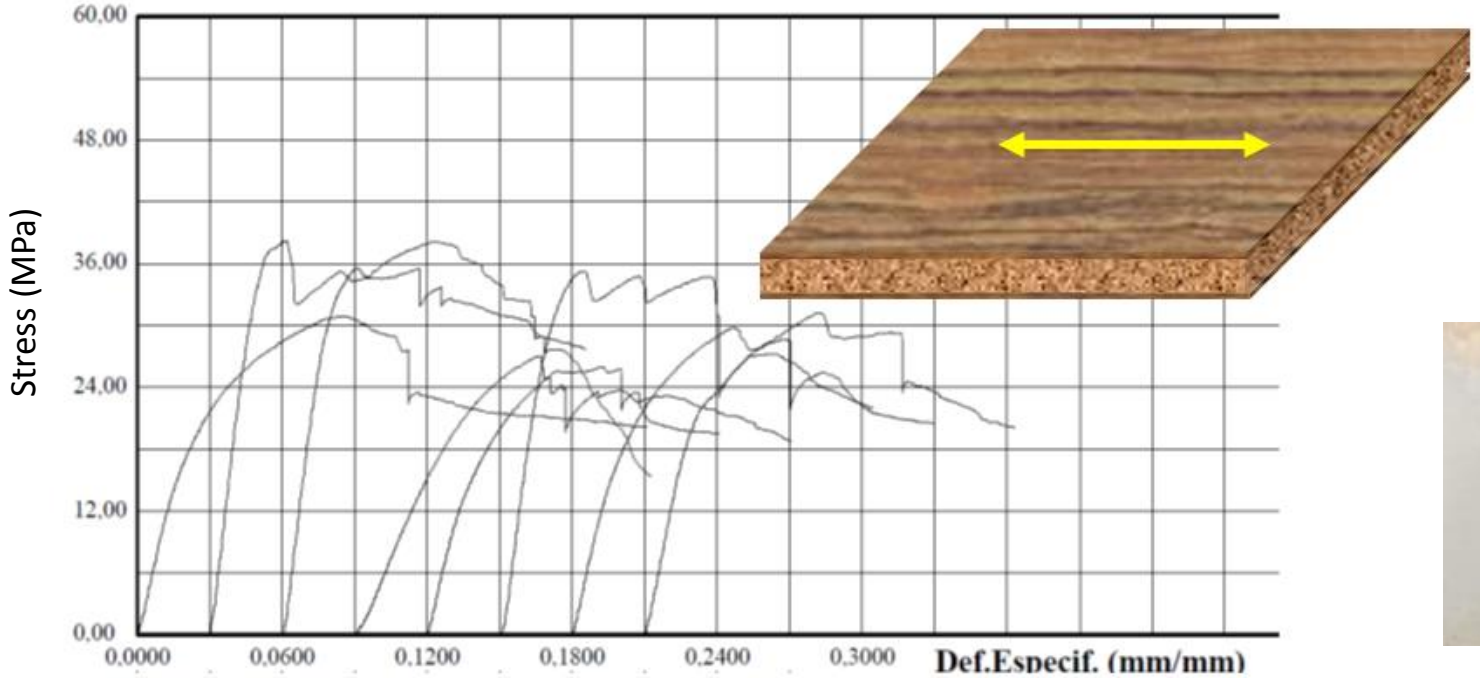
bamboo sandwich panel (under development)

≈ 1100 kg/m³ densified bamboo

resin

550 kg/m³ bamboo particleboard





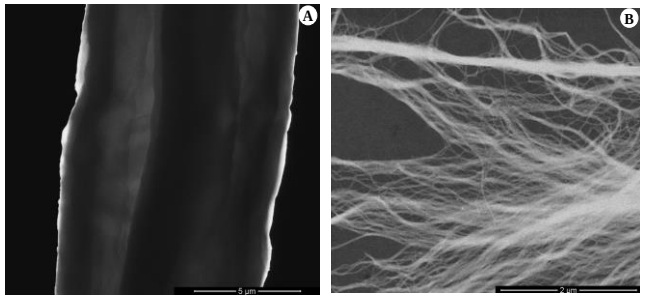
MOR of sandwich panel in Longitudinal direction

Core failure – problems with the particle distribution used for the particleboard

Cellulose

Fiber-cement composites

- ✓ Nanofibrilatted celulose
- ✓ Hybrid fiber-cement composite
- ✓ Filters



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Bamboo poles

- ✓ Structural use
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Particles / Strands / Strips

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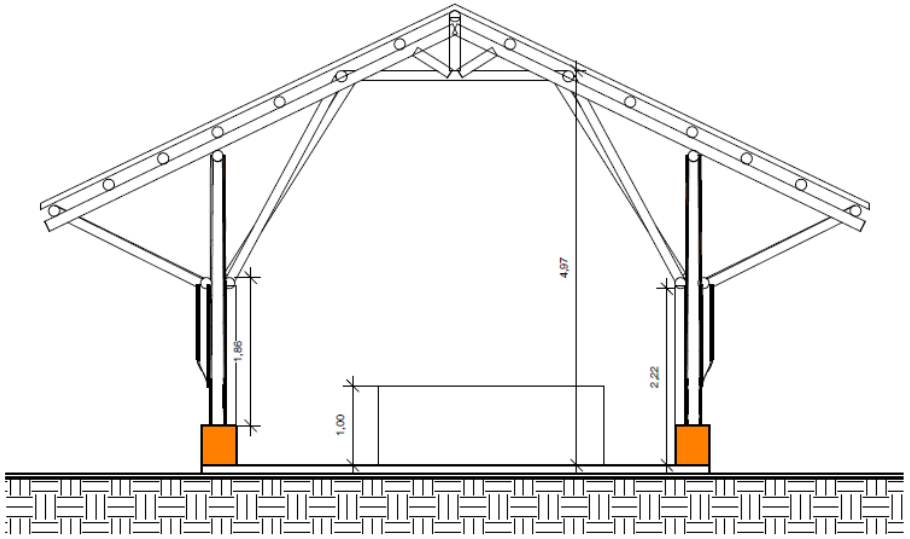
Building solutions: Structure; Roofing; Walling; Flooring

Future plans for our lab – Examples of bamboo structures → Long term evaluation



Project: Arq.
Thales
Pozzer

Thank you for your attention!

Danken!!!

holmersj@usp.br