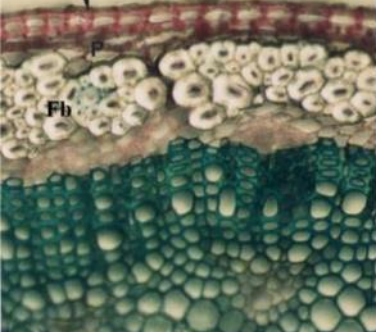




Partie 2

Les biocomposites, propriétés et applications

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IMT Mines Alès

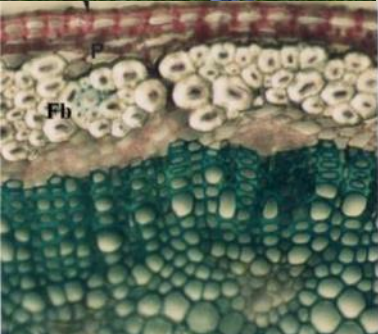
2026-2027



IMT Mines Alès
École Mines-Télécom

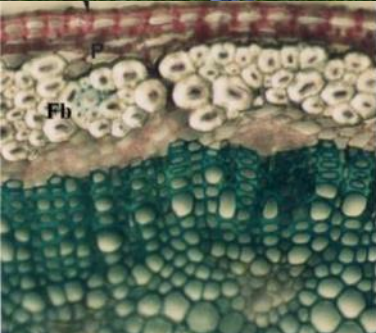


Plan de cours

- 
- **Partie 1 : Matériaux polymères biosourcés / biodégradables**
 - Contexte, définitions, enjeux
 - *Les agropolymères*
 - *Les biopolymères de synthèse*
 - **Partie 2 : les biocomposites, propriétés et applications**
 - Structure et propriétés des fibres végétales
 - Procédés de transformations des fibres et des biocomposites
 - Propriétés et applications des biocomposites
- 
- 
- 

Summary

- **General introduction on composites materials**
- From bioplastics to biocomposites
- Natural fibre structure, properties and processing
- Biocomposites processing & properties
- Market & applications



What is a composite material ?

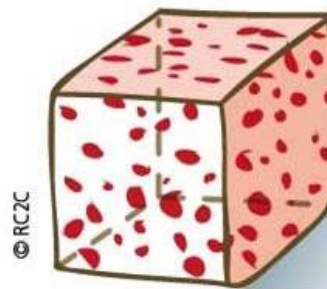
**Combination of a polymer matrix and a reinforcement
(particles, fibres)**

Matrix

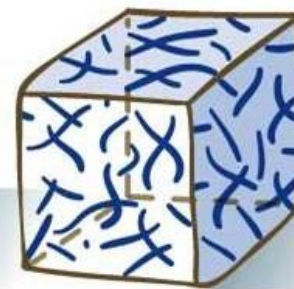
Interface

Reinforcement

- Shape the material
- Protect the particles / fibres from chemicals and ageing
- Ensure the load transfert from the matrix to the reinforcement
- Provide stiffness and strength to the material



**Micro- or
nanoparticles**



Short fibres



Long fibres

Composite industry



Substitution of traditional materials by composite materials

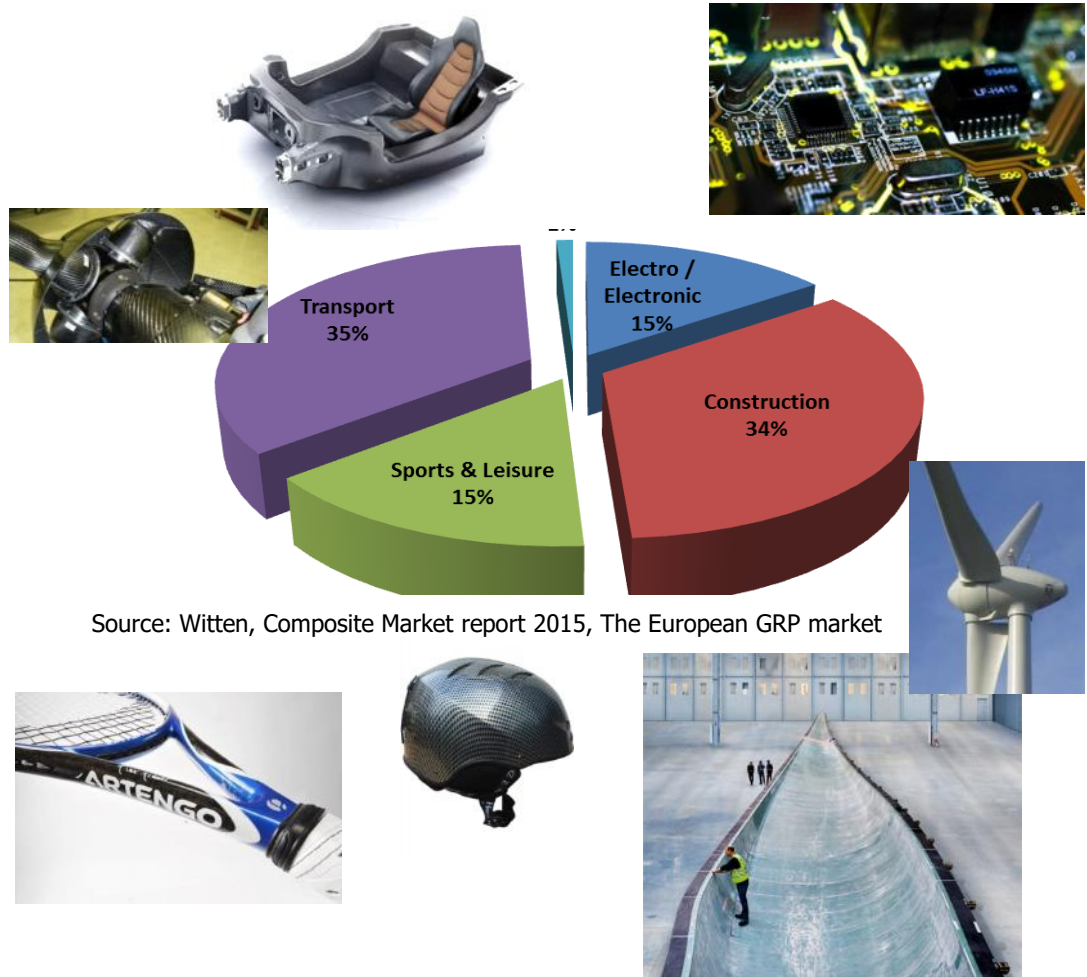
Main share of composite materials are reinforced by glass fibres

Main share of composite materials are based on thermosets

Polyester

Epoxy

Applications of Glass fiber Reinforced Plastics (GRP) in 2015



➤ **Main driver of growth is the weight gain on structures !!!**

Why is weight important ?

Economical reasons :

The price of materials is usually defined by the kilogram : **kg/euros**

Producing **higher volume** of materials at **equivalent kg/euros**

Performances and ecological reasons

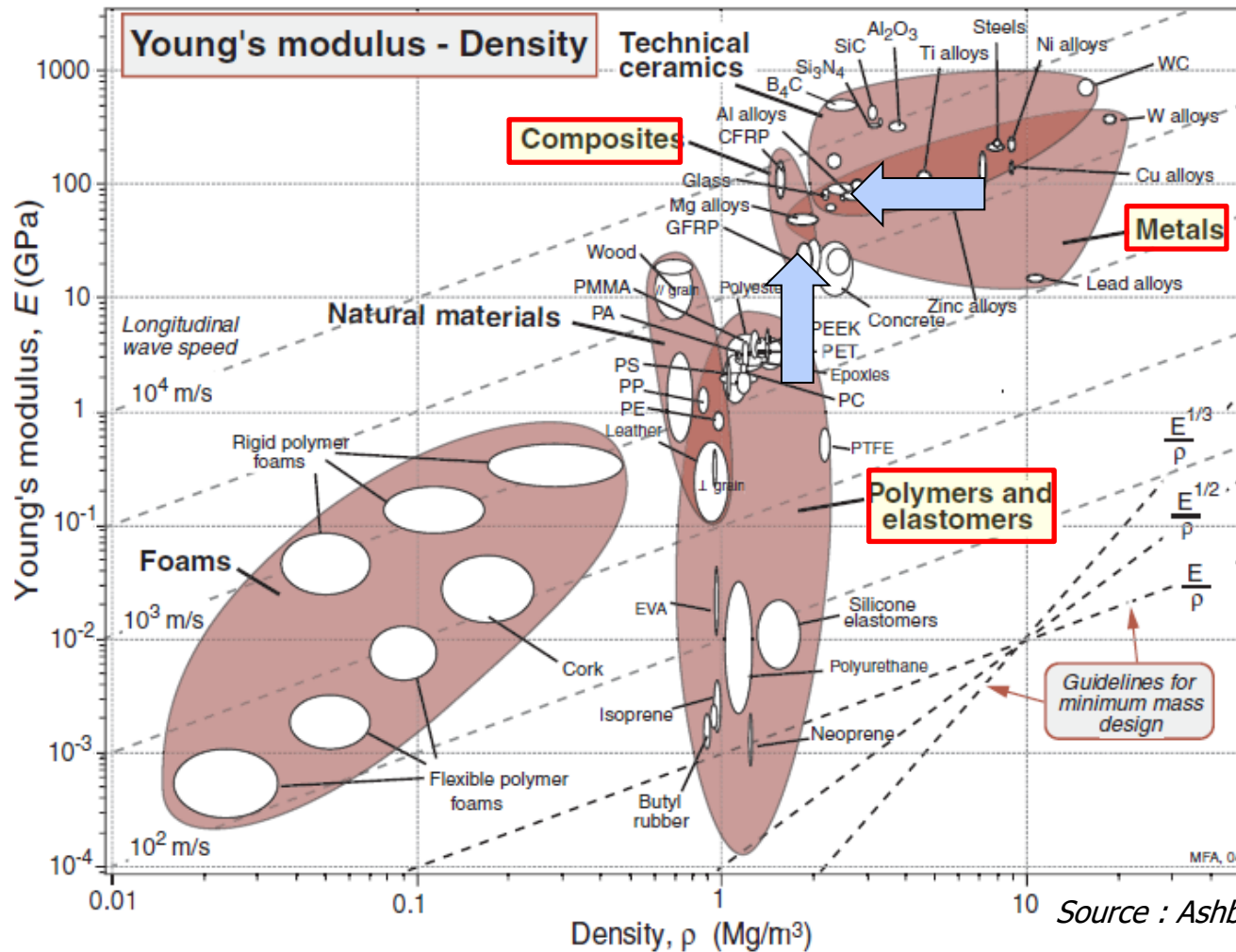
Lighter structures **consume less energy**, especially in the case of moving objects



Carbon bicycle
(Source: Museeuw bikes)



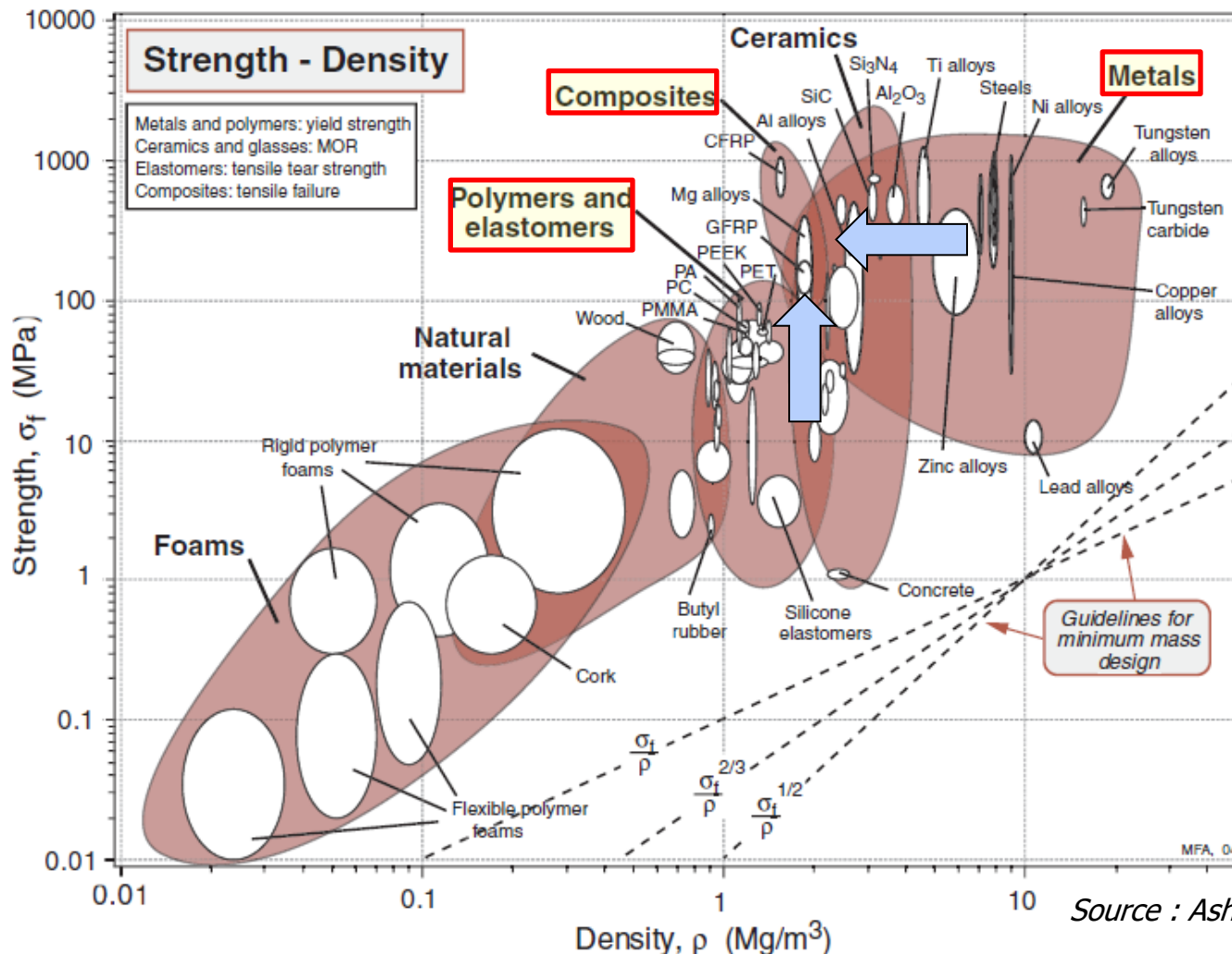
Why is weight important ?



**higher stiffness
than polymers and
lower density
than metals**

Source : Ashby, 2005, Materials design

Why is weight important ?

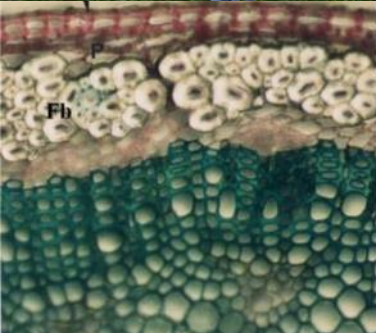


**higher strength
than polymers
and lower density
than metals**

- **A perfect combination between the low density of polymers and the high stiffness and strength of reinforcing fibres**

Summary

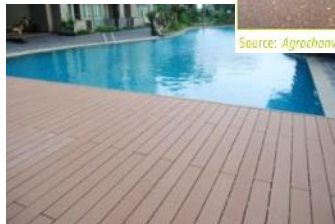
- General introduction on composites materials
- **From bioplastics to biocomposites**
- Natural fibre structure, properties and processing
- Biocomposites processing & properties
- Market & applications



Biodegradable or durable biobased plastics ?

- High demand for **bio-based and biodegradable** plastics (**bioplastics**) in various **industrial sectors**
- Large and growing share of **long-life bio-based products** requiring (**semi-)**structural performance

- Home
- Automotive
- Sports and leisure
- Electronic devices (shells)
- Textiles / apparel



Source: Agrochanvre



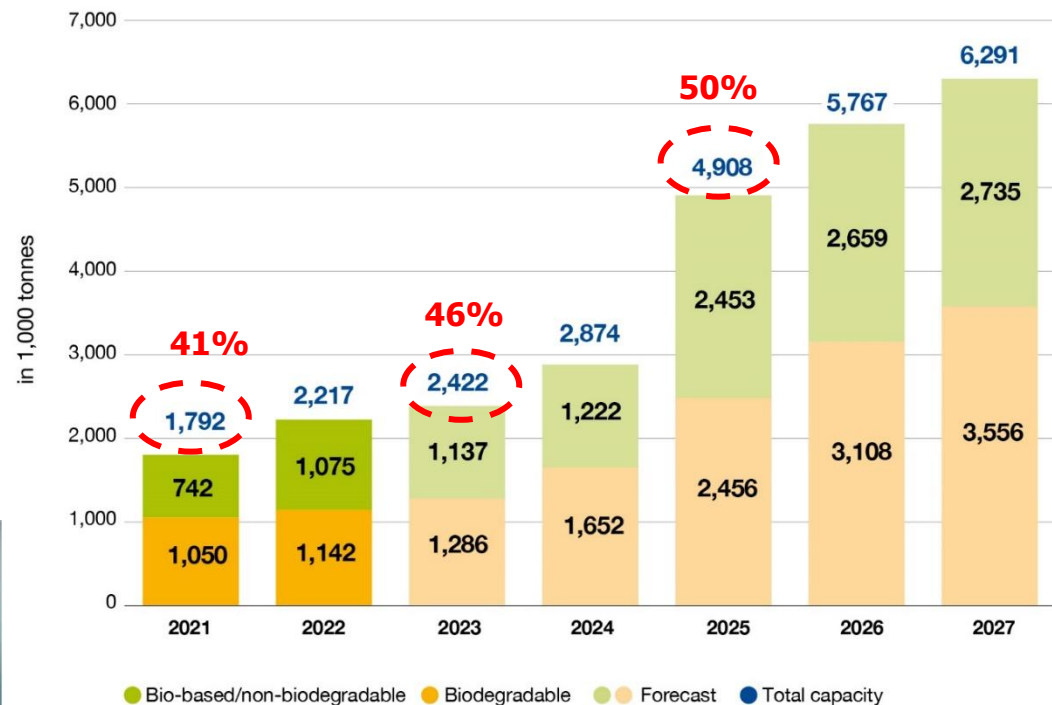
Source: FiberShell



Source: Notax



Global production capacities of bioplastics



Source: European Bioplastics, nova-Institute (2022). More information: www.european-bioplastics.org/market and www.bio-based.eu/markets

Why are natural fibres reinforced composites interesting ?

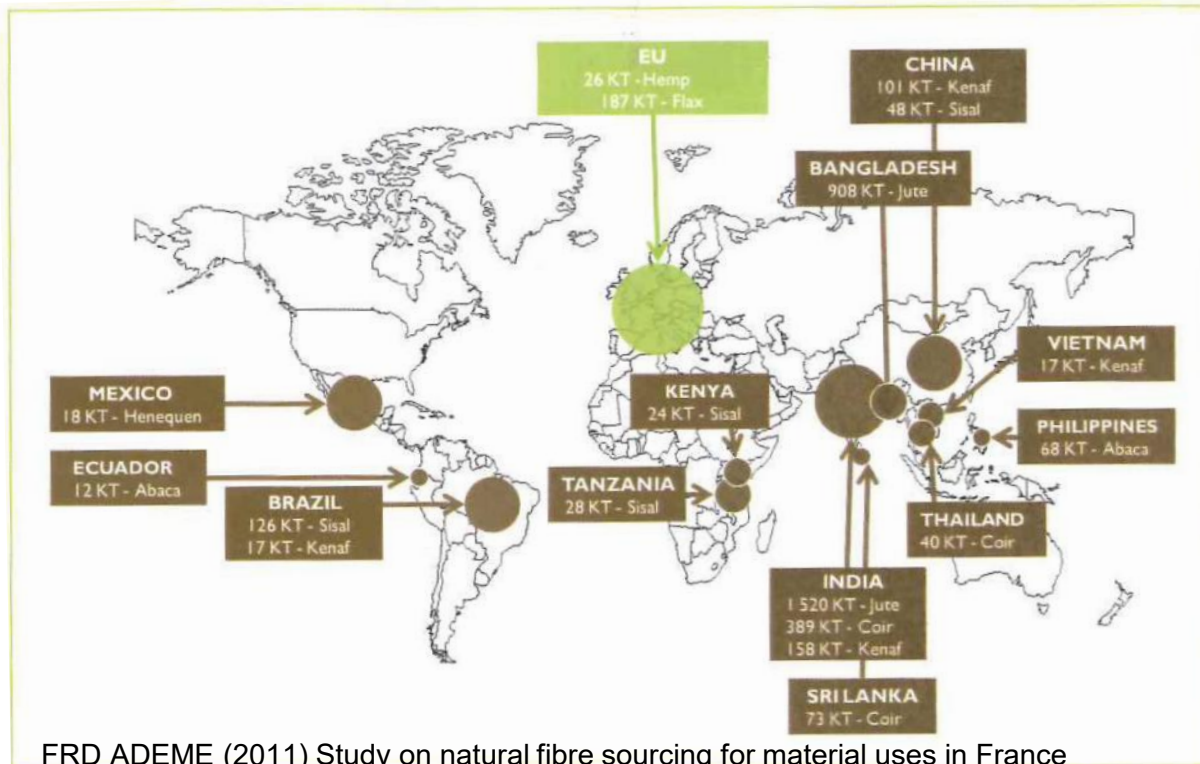
- Needs for **biobased and biodegradable reinforcements** in bioplastics
- Natural fibres (i.e. plant fibres) present several advantages to reinforce polymers:
 - Diversity of fibres and fillers as reinforcements in materials:



Fig. 1. Fibers and fillers from renewable and sustainable resources.

Why are natural fibres reinforced composites interesting ?

- Needs for **biobased and biodegradable reinforcements** in bioplastics
- Natural fibres (i.e. plant fibres) present several advantages to reinforce polymers:
 - Renewable and available resource all over the world :



FRD ADEME (2011) Study on natural fibre sourcing for material uses in France

- Sustainable development of natural fibres must be based on the local valorisation of agrosources to limit transportation (cost and energy consuming)
- Flax and Hemp are the most available fibres in Europe (85% of worldwide production)

Why are natural fibres reinforced composites interesting ?

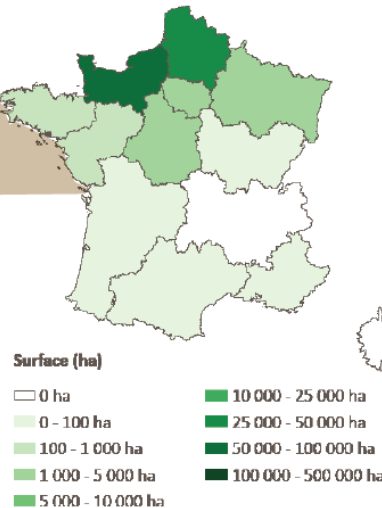
- Needs for **biobased and biodegradable reinforcements** in bioplastics
- Natural fibres (i.e. plant fibres) present several advantages to reinforce polymers:
 - Various culture in France:

Production area

Fibre flax in France (average 2021-2013)

Surface area **124 136 ha/year**
0.47% of UAA

Straw yield
theoretically available
4.8 tMB/ha



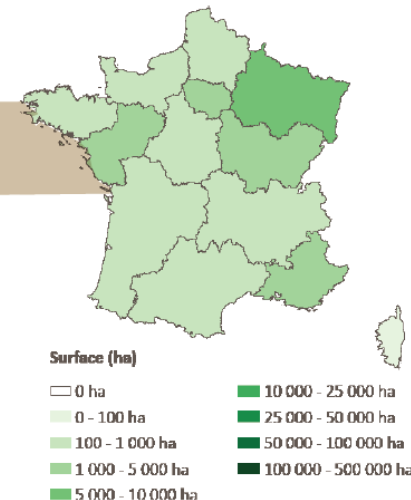
FRD-CODEM (2025) Market overview “Plant fibres
for material use (excluding wood)”

Production area

Hemp in France (average 2021-2013)

Surface **19 253 ha/year**
0.07 % of UAA

Straw yield
theoretically available
7.1 tMB/ha



- Sustainable development of natural fibres must be based on the local valorisation of agrosources to limit transportation (cost and energy consuming)
- Flax and Hemp are the most available fibres in Europe (85% of worldwide production)

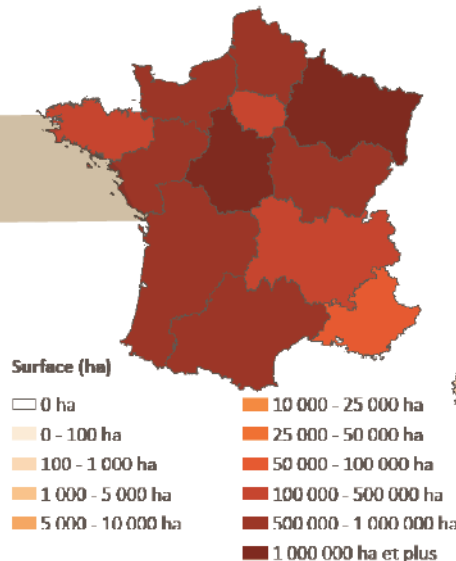
Why are natural fibres reinforced composites interesting ?

- Needs for **biobased and biodegradable reinforcements** in bioplastics
- Natural fibres (i.e. plant fibres) present several advantages to reinforce polymers:
 - Various culture in France:

Production area

Cereal straw in France (average 2021-2013)

Surface **7.3 million ha/year**
28 % of UAA
Straw yield
theoretically available
3.1 tMB/ha

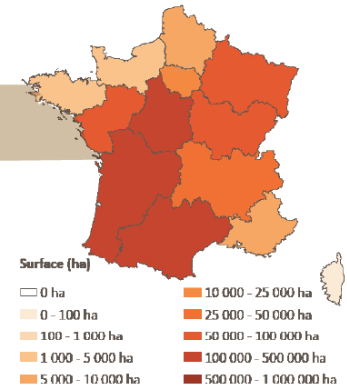


FRD-CODEM (2025) Market overview “Plant fibres
for material use (excluding wood)”

Production area

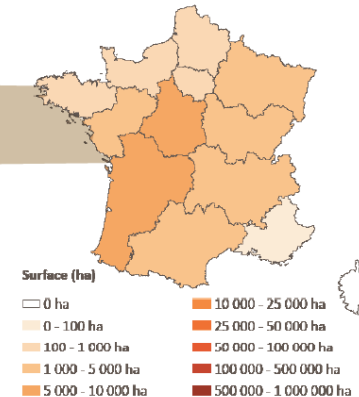
Sunflower stalks in France (average for 2021-2023)

Surface **790 705 ha/year**
3 % of UAA
Biomass yields
theoretically available
1.3 tMB/ha



Oilseed flax straw in France (average 2021-2023)

Surface **31,014 ha/year**
0.1 % of UAA
Straw yield
theoretically available
1.5 tMB/ha



- Sustainable development of natural fibres must be based on the local valorisation of agrosources to limit transportation (cost and energy consuming)
- Flax and Hemp are the most available fibres in Europe (85% of worldwide production)

Why are natural fibres reinforced composites interesting ?

- Needs for **biobased and biodegradable reinforcements** in bioplastics
- Natural fibres (i.e. plant fibres) present several advantages to reinforce polymers:
 - Domestic plant fibres show a stable price level compared to crude oil and standard thermoplastics and other petroleum based synthetic products

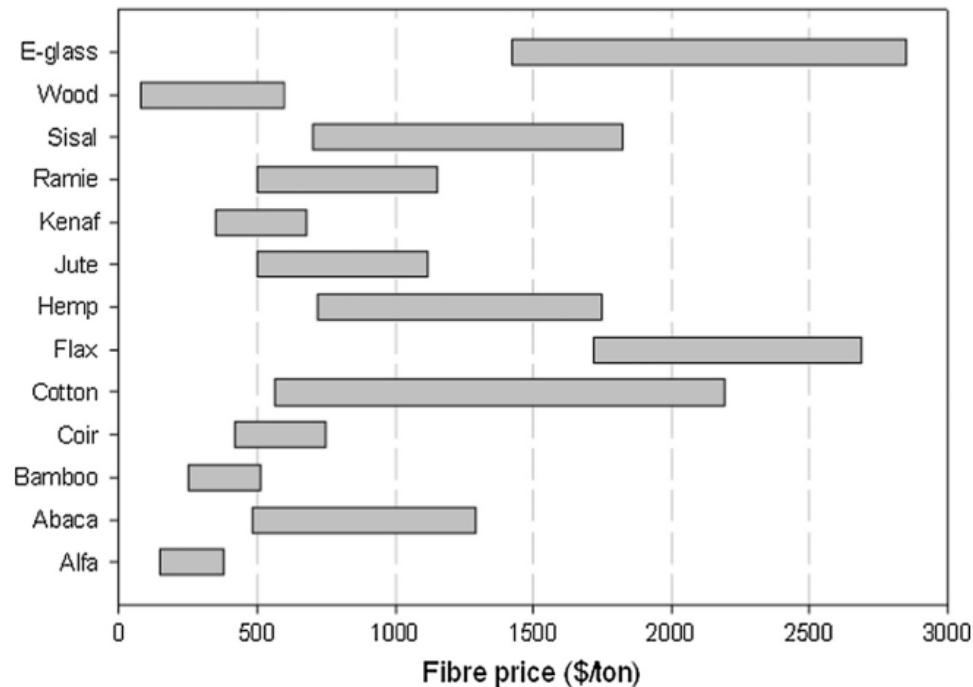
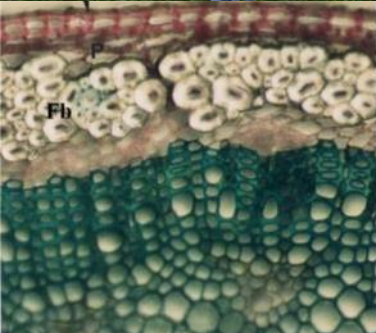


Fig. 3. Commercial prices of vegetal and E-glass fibres (2004–2014 data). These cost values come mainly from the FAO database [32] and are a 2004–2014 range. Price data for flax fibres were provided by Saneco [33] (evolution of scutched fibres market price between 2004 and 2014), [34], bamboo [35] kenaf [35] wood [36] and hemp [37] fibre prices were obtained from literature. In addition, these vegetal fibre cost were compared with e-glass fibre price [38].

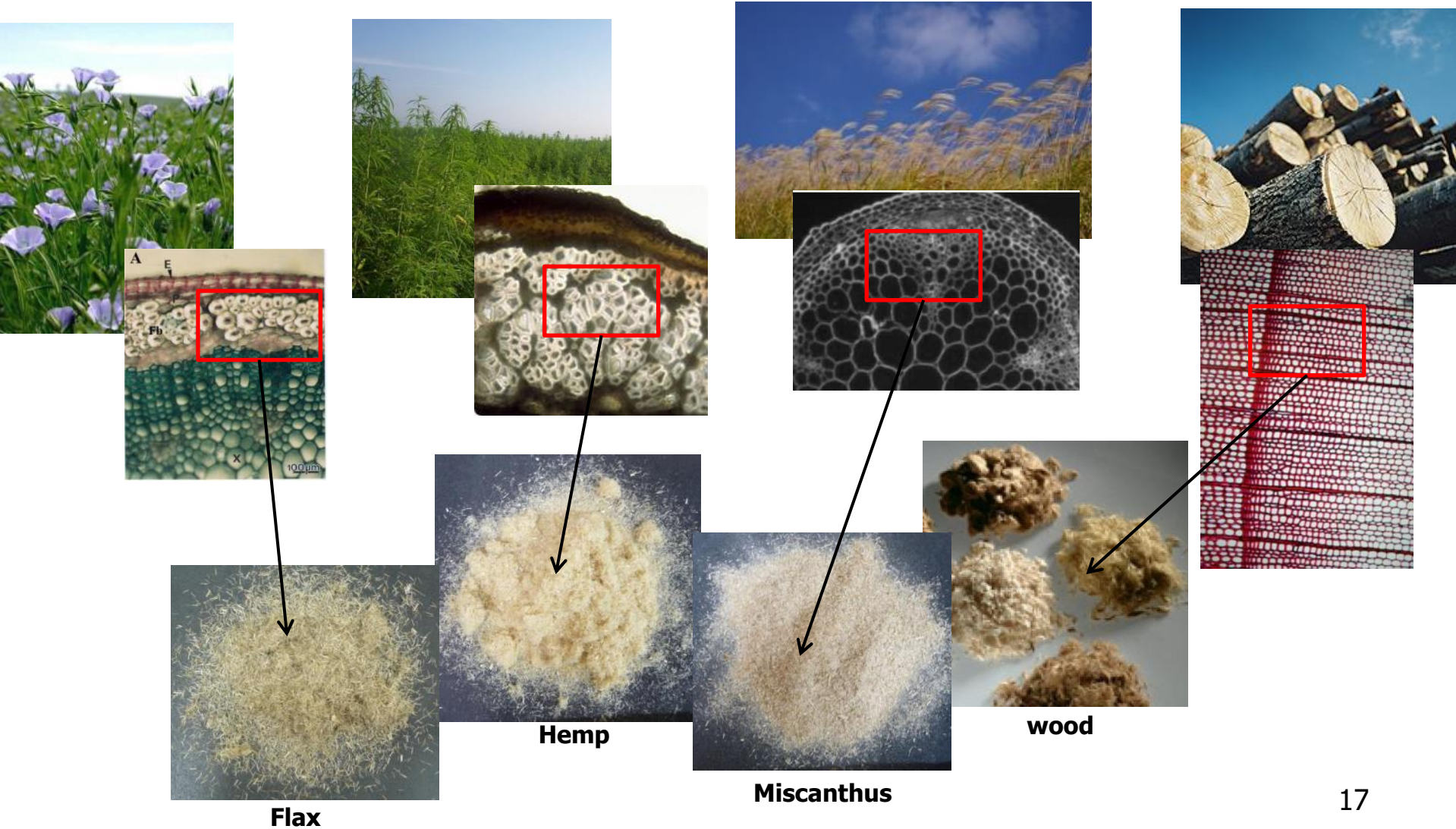
Summary

- Bio-based and biodegradable polymers
- From bioplastics to biocomposites
- **Natural fibre structure, properties and processing**
- Biocomposites processing & properties
- Market & applications



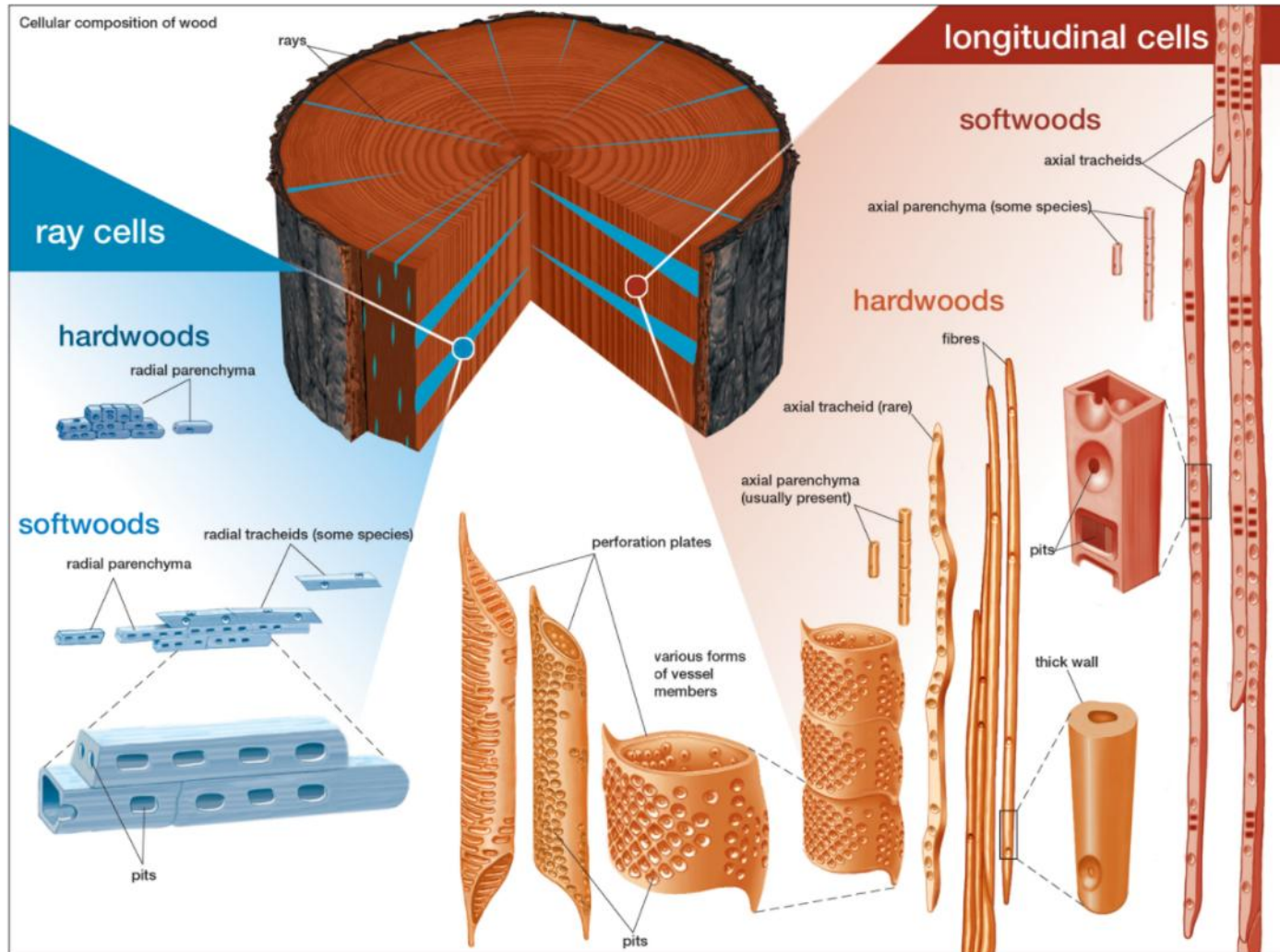
Natural fibres: Botanical origin and structural organisation

Some examples:



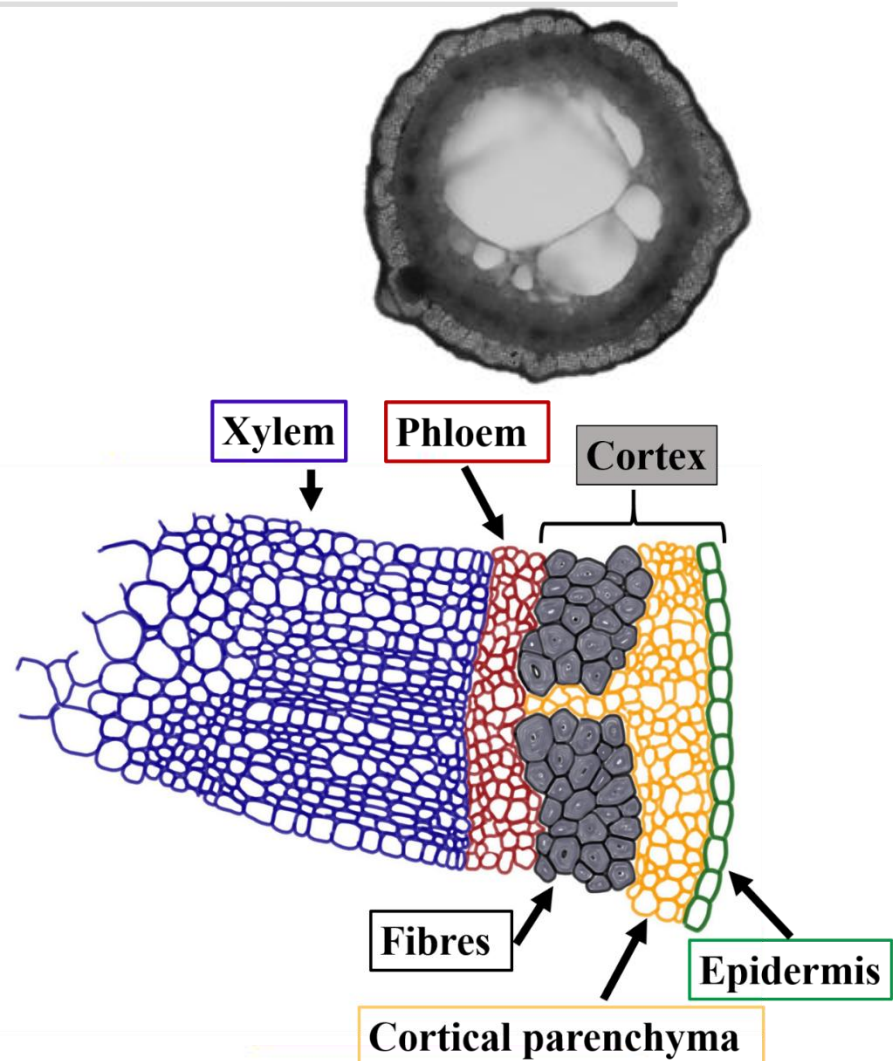
Natural fibres: Botanical origin and structural organisation

A. Anatomy of a tree trunk



Natural fibres: Botanical origin and structural organisation

A. Anatomy of a flax stem



Natural fibres: Botanical origin and structural organisation

Different plant cell structures and morphologies corresponding to different roles in Nature:

- Supporting / **structural** tissues (e.g. bast fibres as flax, hemp, nettle...)
- or **conduction** tissues for sap (e.g. fibres from xylem in wood, phloem for kenaf)

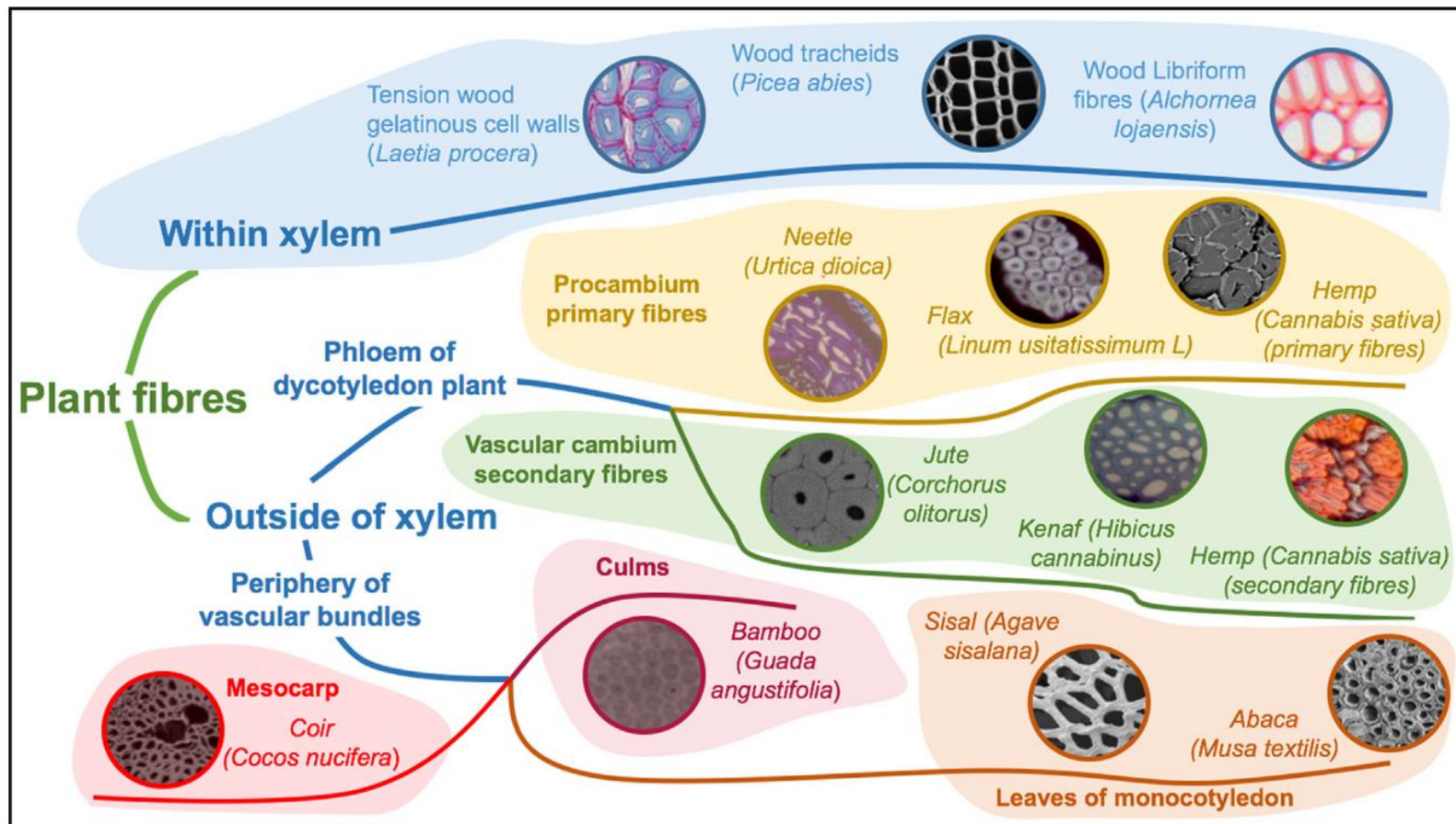


Fig. 25. Classification of plant fibres according to their location in-planta. Plant cell wall cross-sections adapted from [60,97,153–155,158,309–312].

Natural fibres: structural organization from mm to nm

B. Fibre length, thickness and cross sections

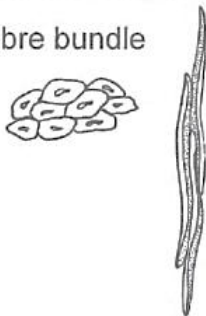
Fibre



		Length	Width
• Ramie	⇒	40 - 260 mm	5 - 126 μm
• Cotton	⇒	10 - 64 mm	12 - 38 μm
• Flax	⇒	4 - 140 mm	2 - 76 μm
• Hemp	⇒	8 - 55 mm	3 - 51 μm
• Abacá	⇒	2 - 12 mm	6 - 46 μm
• Jute	⇒	1 - 6 mm	5 - 30 μm
• Sisal	⇒	0.5 - 8 mm	4 - 47 μm
• Coir	⇒	0.3 - 1.2 mm	12 - 24 μm

(A)

Fibre bundle



(B)

		Length	Width
• Hemp	⇒	650 - 5000 mm	25 - 500 μm
• Jute	⇒	150 - 3600 mm	25 - 200 μm
• Abacá	⇒	60 - 2500 mm	10 - 1000 μm
• Ramie	⇒	800 - 2000 mm	16 - 904 μm
• Flax	⇒	100 - 1500 mm	40 - 620 μm
• Sisal	⇒	40 - 1250 mm	9 - 460 μm
• Coir	⇒	36 - 330 mm	50 - 460 μm
• Cotton	⇒	exists only as single fibre	

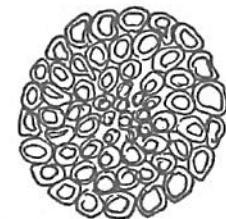
- Single fibre versus fibre bundle
- Variations in dimension (length, width) and aspect ratio
- Variations in cross sections



(A)

Cross sections of cotton fibres

Gossypium hirsutum L.



(B)

Cross section of a coir fibre bundle

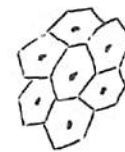
Cocos nucifera L.



(C)

Cross section of a hemp fibre bundle

Cannabis sativa L.



(D)

Cross section of a flax fibre bundle

Linum usitatissimum L.

Natural fibres: structural organization from mm to nm

C. Cell structure : porosity / lumen

- Various percentage of porosity (lumen / total surface ratio)

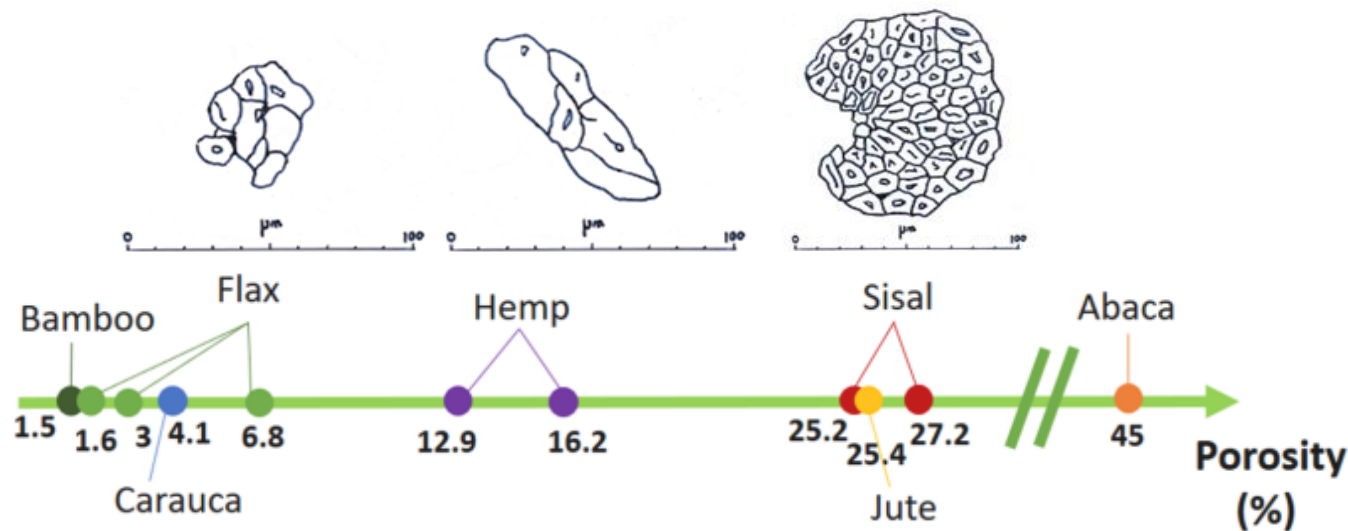
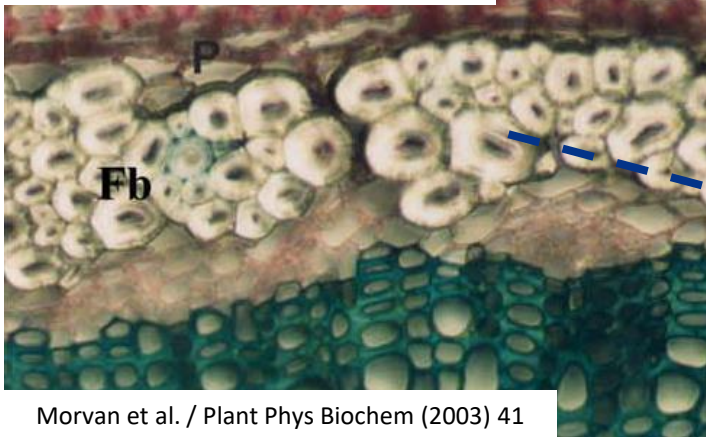


Fig. 6. Percentage of porosity (lumen/total surface ratio) for different plant fibres obtained from transversal observations [22,38,205–209], adapted from [210].

Natural fibres: structural organization from mm to nm

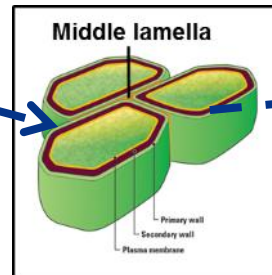
D. Cell wall structure : biochemical composition

Fiber bundles in flax stem

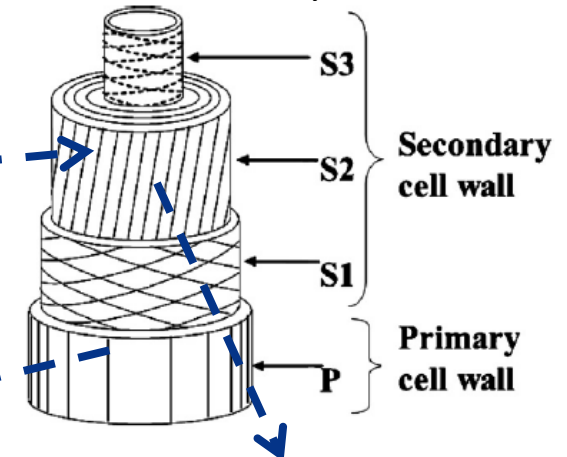


Morvan et al. / Plant Phys Biochem (2003) 41

➤ Bundles of elementary fibers glued by a middle lamellae rich in pectins, lignin



➤ Elementary fibers formed by several layers and walls



Primary wall (P)

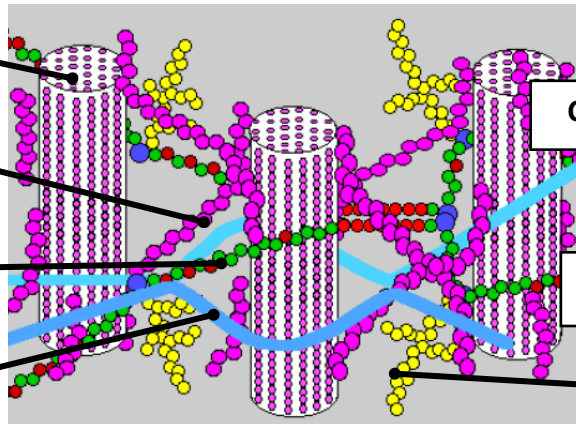
Secondary walls (S1, S2)

Cellulose microfibrils

Hemicelluloses

Pectins

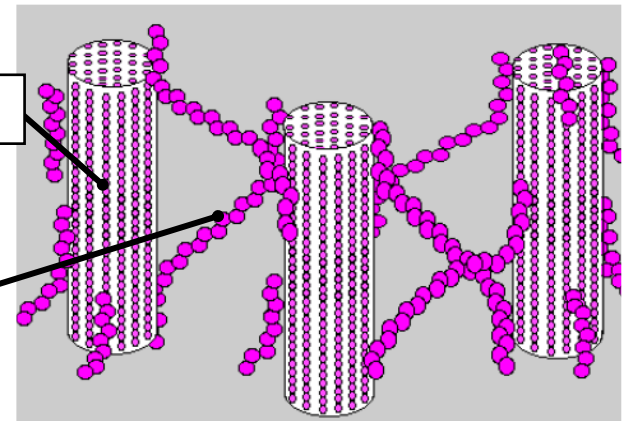
Proteins



Cellulose microfibrils

Hemicelluloses

Lignin



Natural fibres: structural organization from mm to nm

Biochemical composition of selected natural fibres

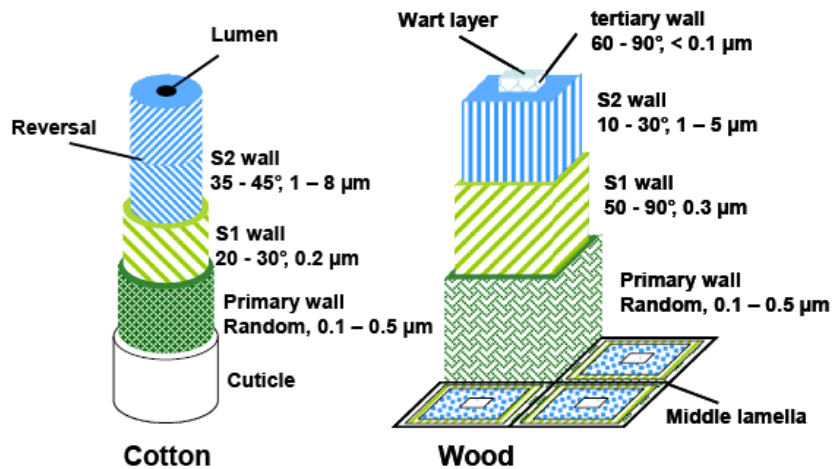
Table 3

Biochemical composition of lignocellulosic fibres.

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Fat and Wax (%)	Reference
<i>Musa textilis</i> (Abaca)	60.8–68.0	17.5–21	5–15.1	< 1	< 1	[73,114,115]
<i>Stipa tenacissima</i> (Alfa)	43.9–48.0	25.7–38.5	14.9–23	1	1–3	[47,48,98,116]
<i>Bambusoideae</i> (Bamboo)	36.1–54.6	11.4–16.6	20.5–28.5	< 1	1–4	[117–119]
<i>Cocos nucifera</i> (Coir)	32.0–43.4	0.3	40–45.8	3	0–6	[53,77]
<i>Gossypium</i> sp. (Cotton)	82.7–98.0	4.0–5.7	0.7	4	2–3	[100,120]
<i>Linum Usitatissimum</i> L. (Flax)	60–85	14.0–20.6	1–3	1.8–15.0	1–6	[121–125]
<i>Cannabis Sativa</i> (Hemp)	55–90	12	2–5	3	1.7	[22,64,126–131]
<i>Corchorus capsularis</i> (Jute)	58.0–71.5	13.6–24.0	11.8–16	2	< 1	[103,132]
<i>Ceiba pentandra</i> (Kapok)	13–35	23–32	13–21	7–23	< 1	[80,81]
<i>Hibiscus cannabinus</i> (Kenaf)	52.0–61.2	18.5–29.7	12.9–16.1	3–5	< 1	[84–86]
<i>Boehmeria nivea</i> (Ramie)	61.8–76.2	5.3–16.7	0.6–9.1	0.3	< 1	[133,134]
<i>Agave sisalana</i> (Sisal)	52.8–65	19.3	11.1–13.5	10–14	< 1	[135,136]
Wood (different species)	38–45	19–39	22–34	0.4–5	< 1	[137–139]

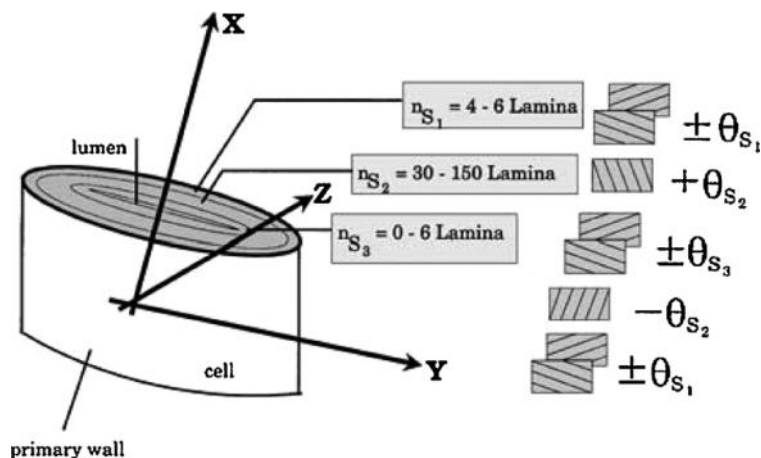
Natural fibres: structural organization from mm to nm

D. Cell wall structure : cellulose microfibrils orientation



➤ Various **microfibrillar angle (MFA)** depending of cell layers and fibre types

➤ Direct impact on mechanical properties



Fiber	Spiral angle [°]	Cellulose content [wt.-%]
Banana	11	65
Coir	30-49	43
Flax	6-10	64-71
Hemp	6	—
Jute	8	61-72
Pineapple	8-14	81
Sisal	10-25	66-70
Ramie	8	69-83



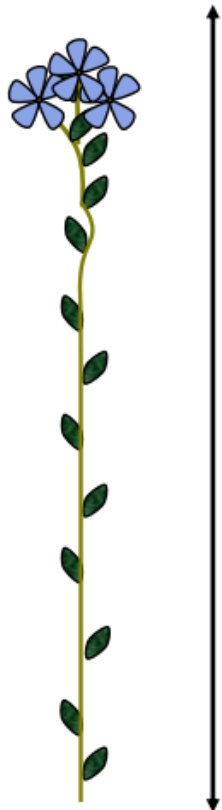
Summary

- Bio-based and biodegradable polymers
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- Market & applications

Natural fibres: properties

A. Outstanding *in-vivo* mechanical properties (example of flax)

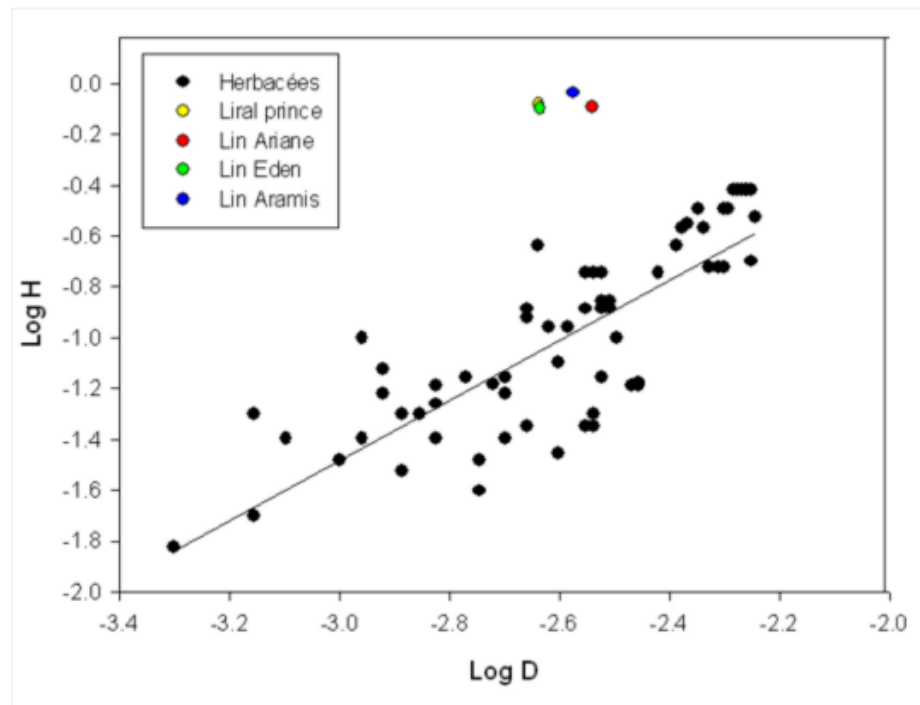
La tige de lin possède un élancement exceptionnel



Hauteur 1000 mm

Diamètre 2/3 mm

Rapport d'aspect: $1000 : 3 = 333$



Natural fibres: properties

A. Outstanding *in-vivo* mechanical properties (example of flax)

Plus performant que les arbres les plus hauts !



Hauteur 1000 mm
Diamètre 3 mm

Rapport d'aspect: $1000 : 3 = 333$



Séquoia Géant: 120 m pour un
diamètre de 6-8 mètres environ

Rapport d'aspect: $120 : 6 = 20$

Si le lin avait le
diamètre du Séquoia:

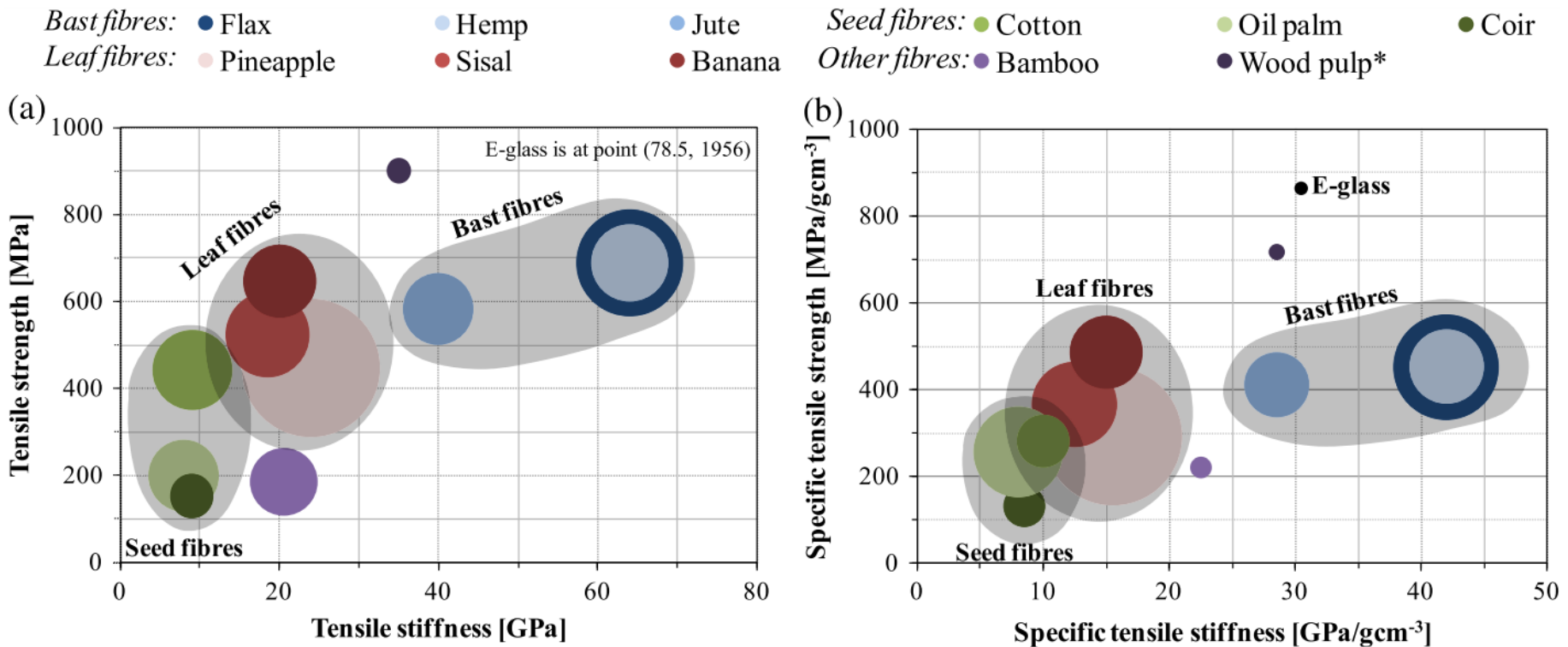
Il ferait environ 2 Km
de haut !



Natural fibres: properties

B. Mechanical properties of selected natural fibres

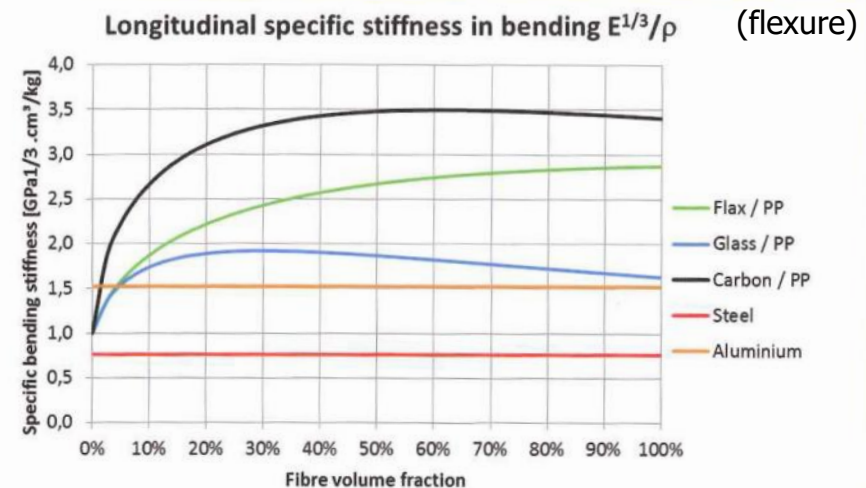
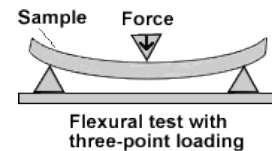
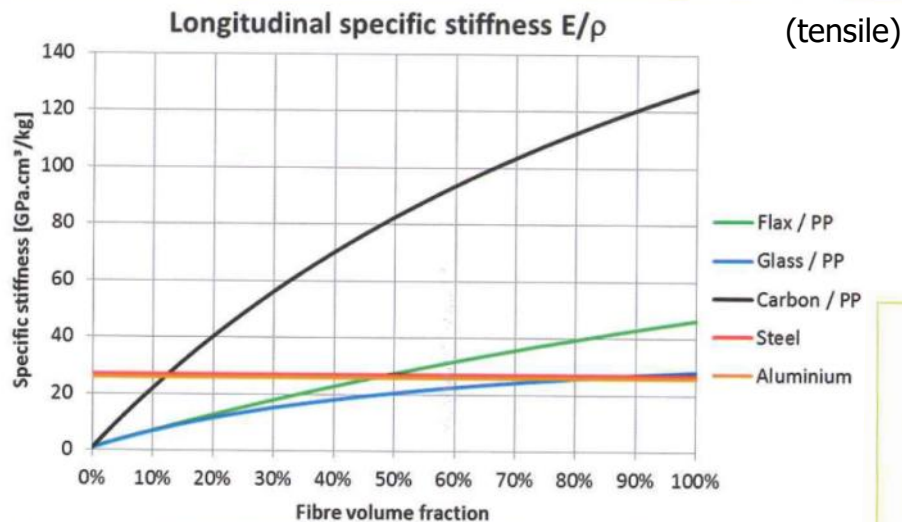
- Flax and hemp fibres show interesting **specific properties** as compared to glass fibres



Natural fibres: properties

B. Mechanical properties of selected natural fibres

- Good specific stiffness and strength compared to glass fibres and metals :



Natural fibres: properties

B. Mechanical properties of selected natural fibres

Mechanical properties of lignocellulosic fibres elements (elementary fibres or bundles).

	Elementary fibre or bundle	Diameter (µm)	Young's Modulus (GPa)	Strength at break (MPa)	Strain at break (%)	Reference
<i>Musa textilis</i> (Abaca)	Bundle	179–230	17.1–18.4	755–798	8.8–6.2	[96,97]
<i>Stipa tenacissima</i> (Alfa)	Elementary and bundle	24.3	31.0–71.0	679–1480	2.4–2.8	[48,98]
<i>Bambusoideae</i> (Bamboo)	Elementary	13.4	32.0–43.7	1200–1610	3.8–5.8	[49,50]
<i>Cocos nucifera</i> (Coir)	Bundle	100–460	3.39–17.3	131–343	3.7–44.7	[53,54,76,99]
<i>Gossypium</i> sp. (Cotton)	Elementary	No bundle	5.5–13.0	287–800	3–10	[57,100]
<i>Linum Usitatissimum</i> L. (Flax)	Elementary	12.4–23.9	37.2–75.1	595–1510	1.6–3.6	[21,23,59,60,101]
<i>Cannabis Sativa</i> (Hemp)	Elementary/Bundle	10.9–42.0	14.4–44.5	285–889	0.8–3.3	[22,66–71,102]
<i>Corchorus capsularis</i> (Jute)	Bundle	60–110	10–31.2	114–629	1.5–1.8	[57,78,103,104]
<i>Ceiba pentandra</i> (Kapok)	Elementary	23.6	1.7–4.0	45–93	1.2–4.0	[80,81]
<i>Hibiscus cannabinus</i> (Kenaf)	Elementary	13.3	19	983	4.5	[105]
<i>Boehmeria nivea</i> (Ramie)	Elementary	34–50	24.5–65	560–900	1.2–2.5	[58,90,106]
<i>Agave sisalana</i> (Sisal)	Bundle	25–252	9.0–25.0	347–577	2.3–5.45	[70,91,107,108]
Wood (different species)	Elementary	15.5–22.6	15.4–27.5	553–1300	3–7	[109–113]

Natural fibres: properties

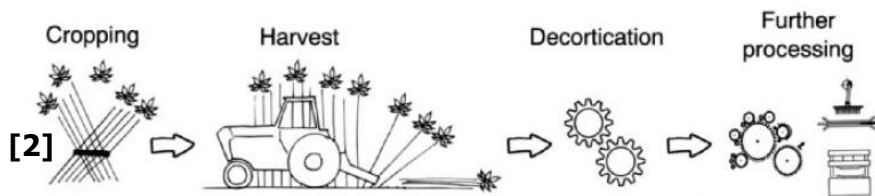
C. Origins of variations in mechanical properties

Mechanical behaviour related to

- Cell structure : botanical origins and role in planta

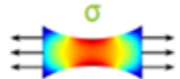


- Growing, harvesting and processing conditions

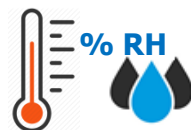


Experimental factors...

- Measurement methods

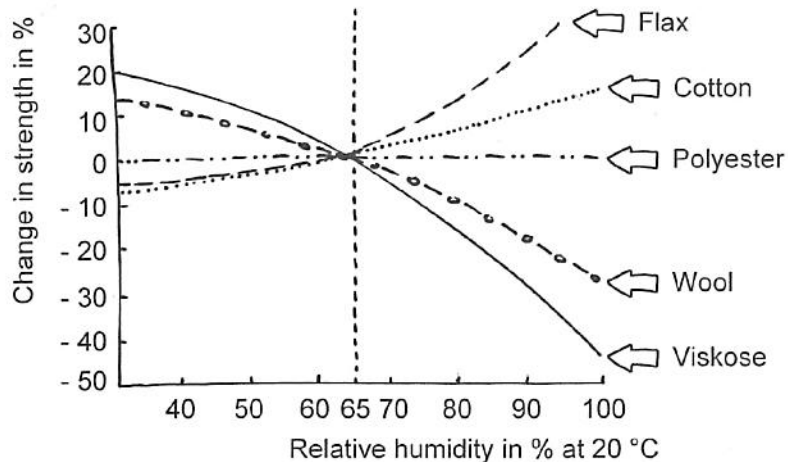


- Hygro/hydrothermal conditions



Natural fibres: properties

D. Effect of relative humidity



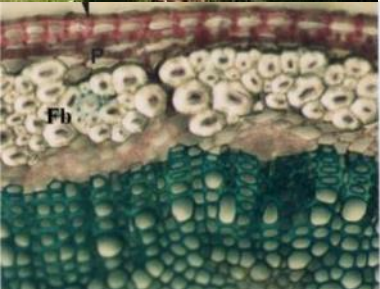
- Fibre properties are greatly influence by the relative humidity (RH)
- Depending of the fibres : variations in modulus, strength and dimensions as a function of RH

Properties	Flax	Jute	Sisal	Cotton
Absorption regain in % at 65% relative humidity and 20 °C	7-12	8.5-17	10-22	7-25
Transverse swelling in %	20-25	20-22	18.20	7-20
Axial swelling in %	0.05-0.2	0.37		1.1-2.8
Volume swelling in %	29.5	44-45	39.5	34-44
Water retention in %	50-55	25-35	30-45	45-50



Summary

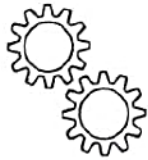
- 
- 
- Bio-based and biodegradable polymers
 - From bioplastics to biocomposites
 - **Natural fibre structure, properties and processing**
 - Biocomposites processing & properties
 - Market & applications



Natural fibres : extraction and uses

A. Different separation techniques for fibre bundles

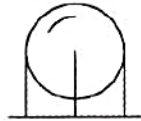
Physical separation



Mechanical separation



Physical/chemical separation



Steam explosion separation



Ultrasonic separation



Chemical separation



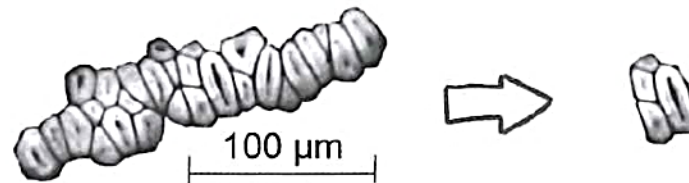
NaOH separation



Microbiological separation



Enzymatical separation



Natural fibres processing and uses

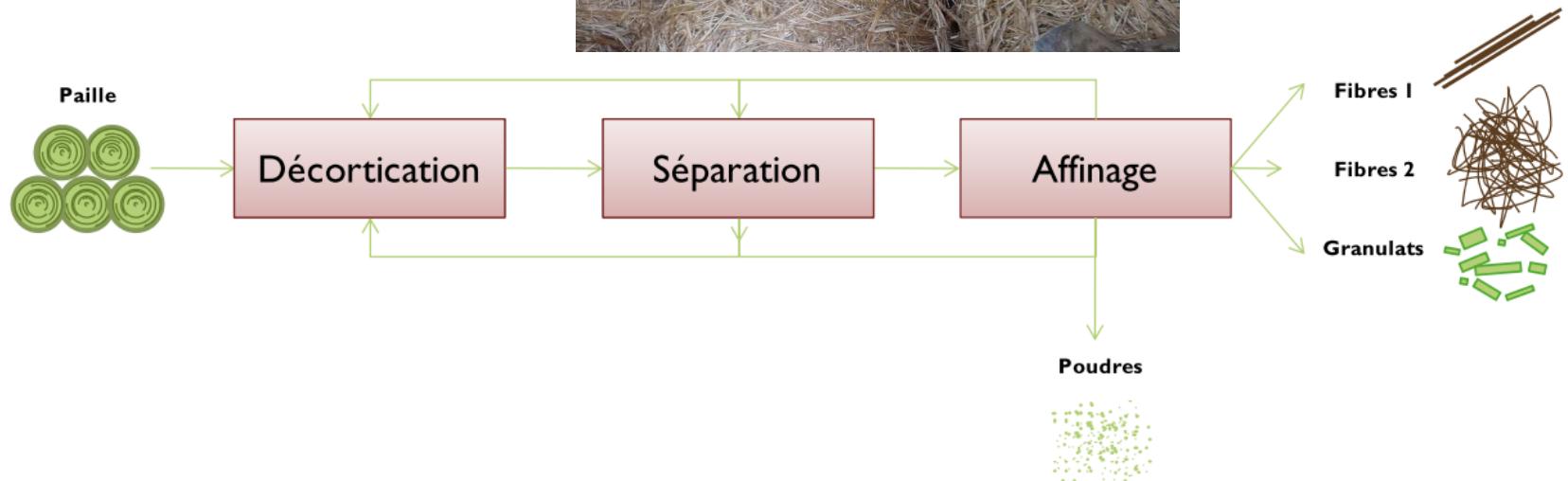


Figure 4 – Processus générique d'extraction des fibres végétales [source FRD]

Natural fibres processing and uses

B. Various morphologies : from fibres (mm to dm) to flours/fillers (μm)

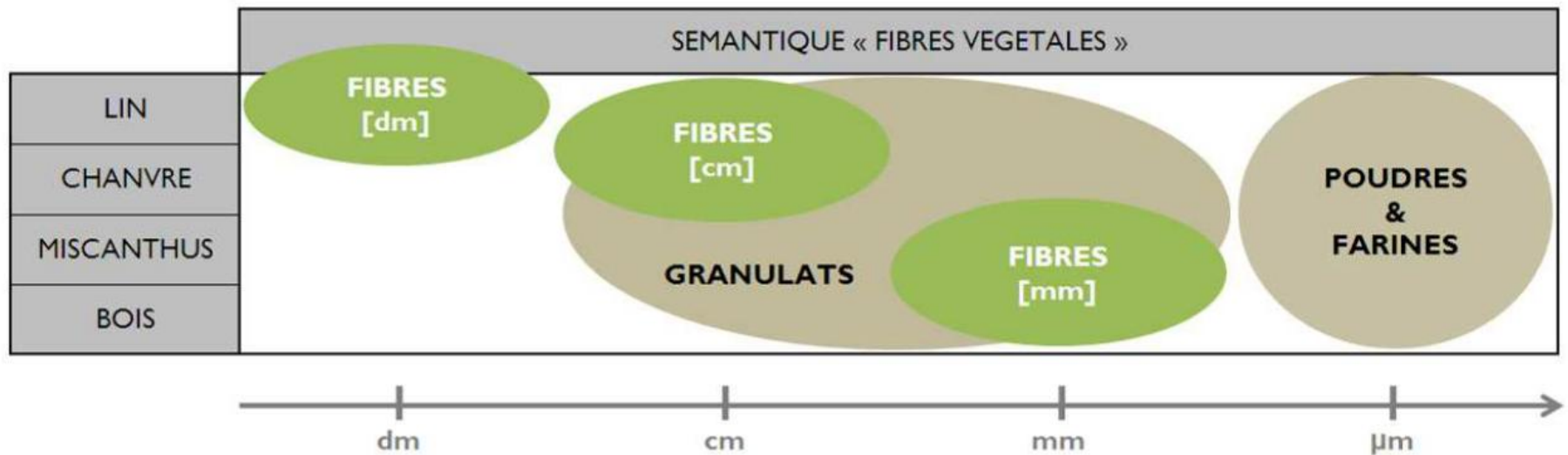


Figure 6 – Proposition d'une nouvelle sémantique des fibres végétales [source FRD]

Natural fibres processing and uses

C. Case of flax : Main semi-products used in composite applications

Depending of the applications and composite processing the following natural fibre semi-products are used :

Short fibres



Non-woven fabrics



Roving



Woven fabrics



- Unidirectional 0°
- Cross-ply 0° / 90°
- Biaxial -45° / 45°
- Multiaxial

Natural fibres processing and uses

D. Relation reinforcement's specificities / composite's architecture

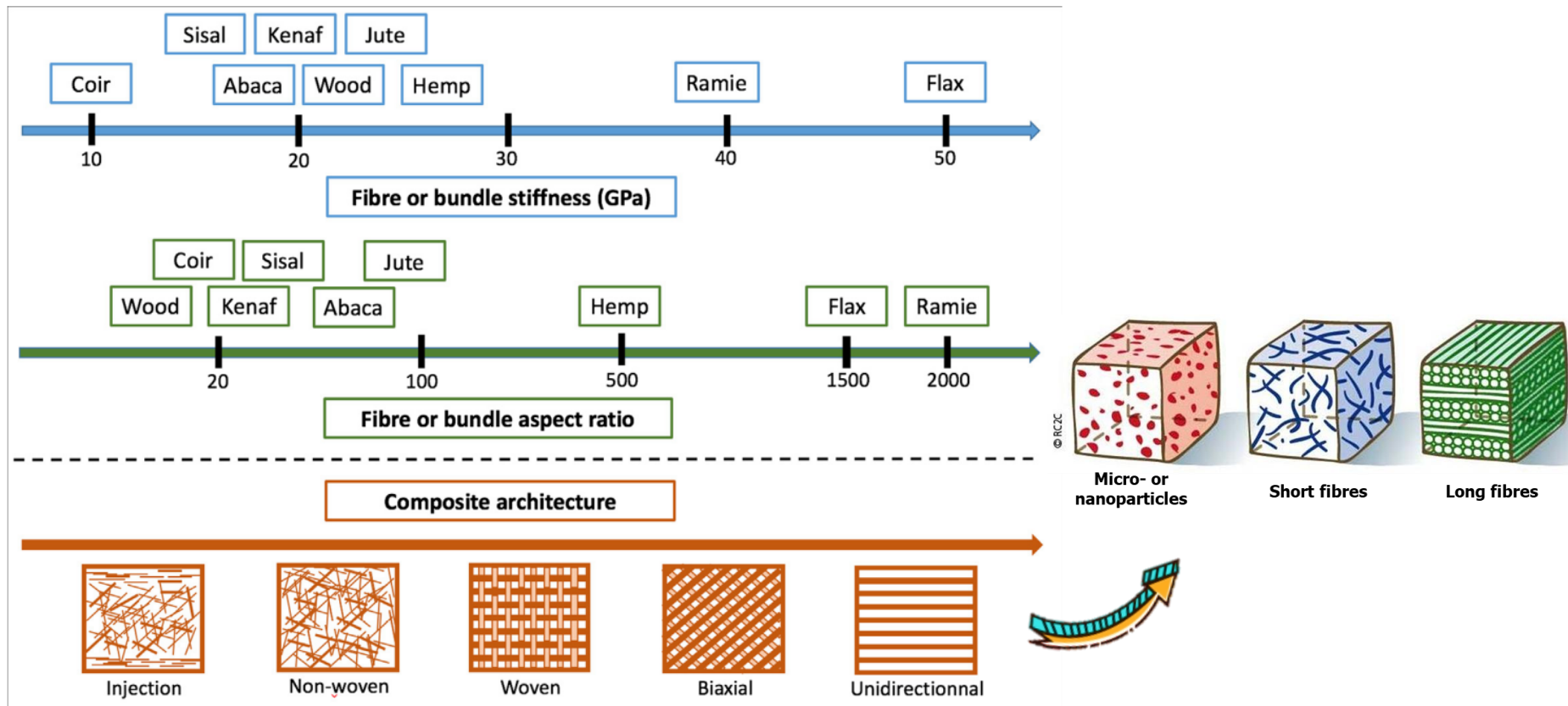
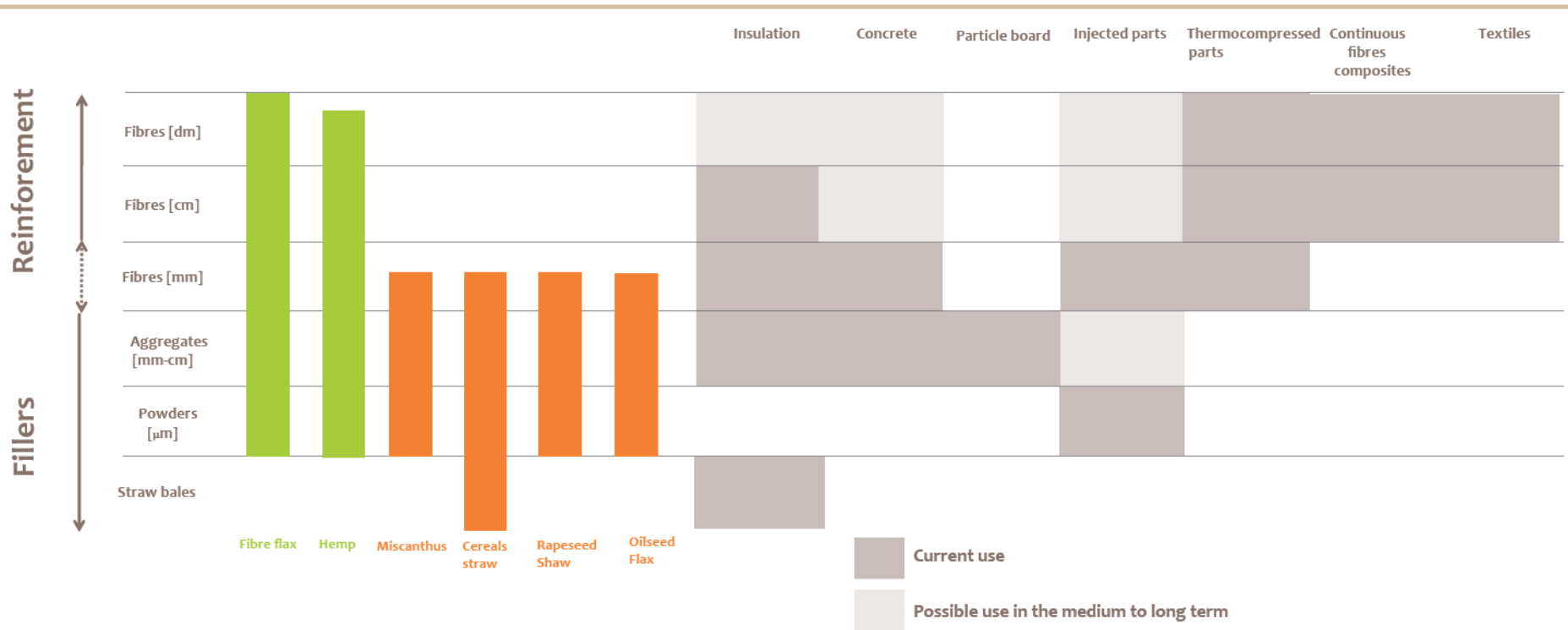


Fig. 36. Panorama of plant reinforcement's mechanical or morphological specificities and composite's architecture diversity.

Natural fibres processing and uses

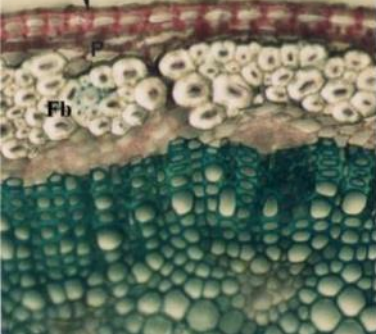
D. Relation reinforcements / processing / applications



Degree of readiness for the use of plant fibres in materials in France (source: FRD-CODEM 2025/Steering Committee)



Summary

- 
- Bio-based and biodegradable polymers
 - From bioplastics to biocomposites
 - Natural fibre structure, properties & processing
 - **Biocomposites processing & properties**
 - Market & applications
- 
- 



Biocomposites processing

A. Main processing routes for biocomposites

Composite processing & manufacturing are highly conditioned by the type of matrix used:

- Thermoplastics (melting): polyethylene PE, polypropylene PP, biopolyesters (PLA, PBS, PHAs...)
- Thermosets (curing): epoxy, vinylenes, polyesters

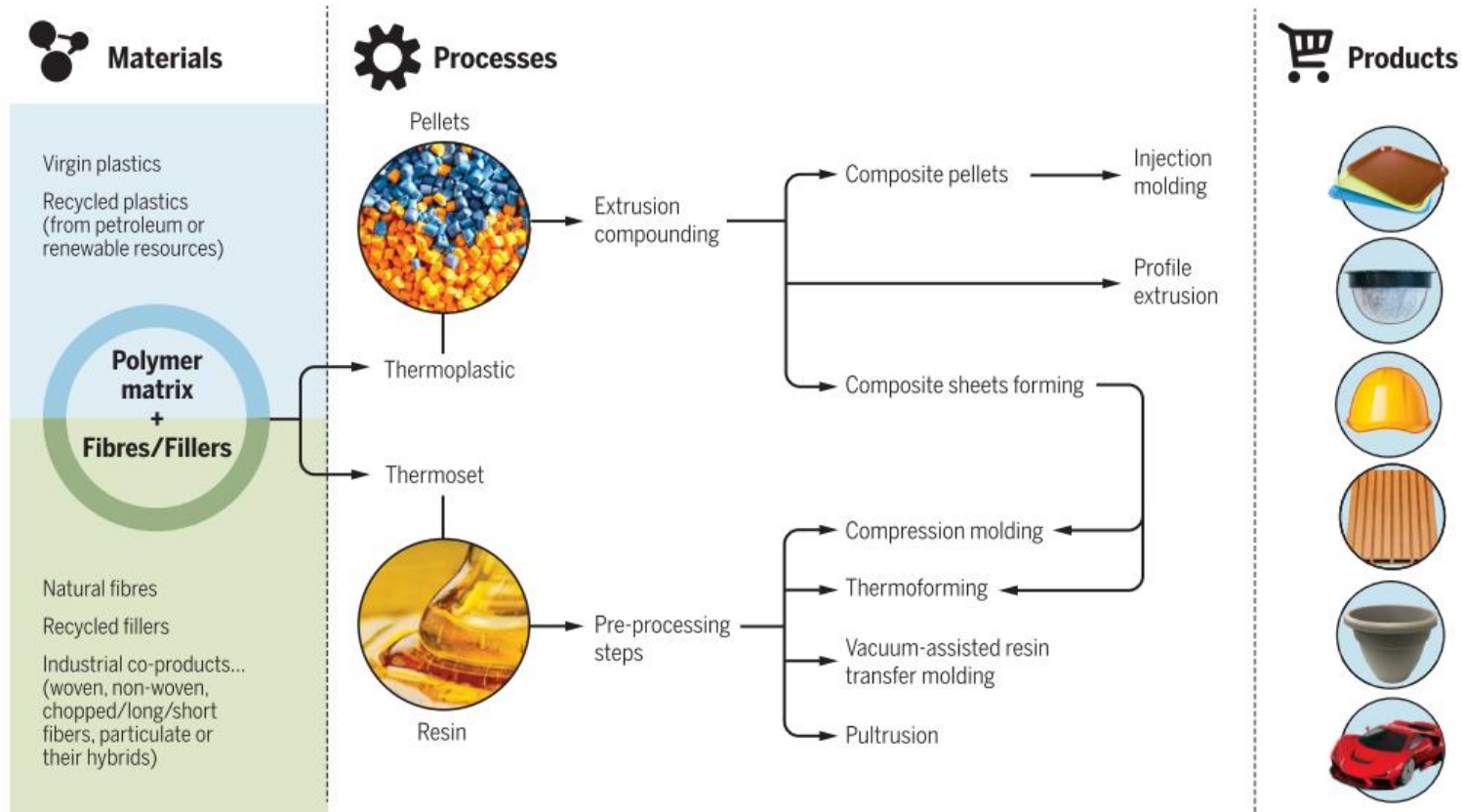
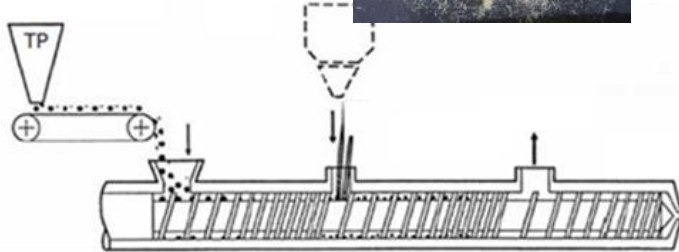


Fig. 4. Biocomposite product examples: From raw materials to manufacturing.

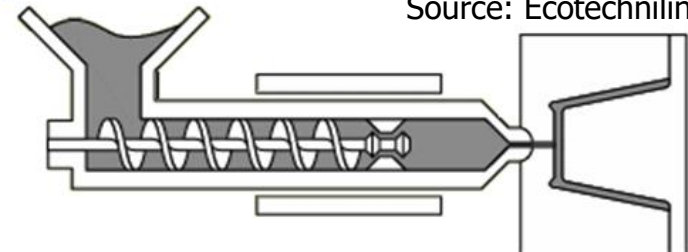
Thermoplastics biocomposites

A. Short fibre compounds

1. Mixing matrix and fibres



2. Shaping of the compound



Source: AFT plasturgie

Thermoplastics biocomposites

B. Commingled fabrics and thermoplastic prepregs

Commingled flax – polypropylene fibres

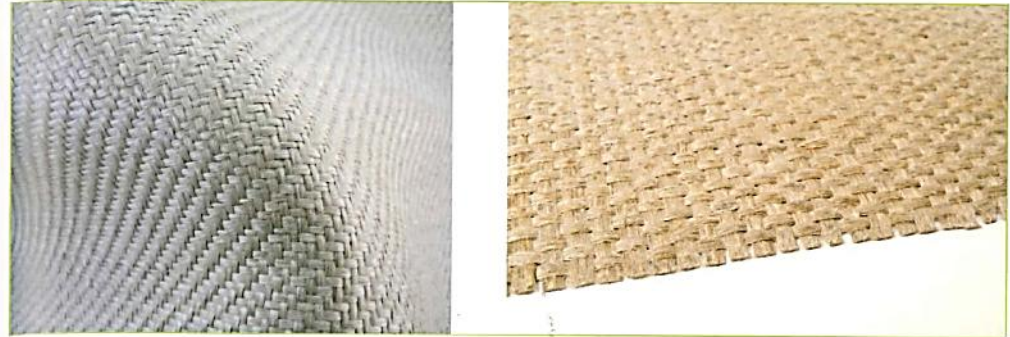
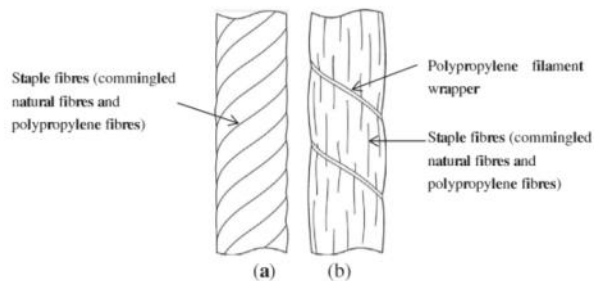
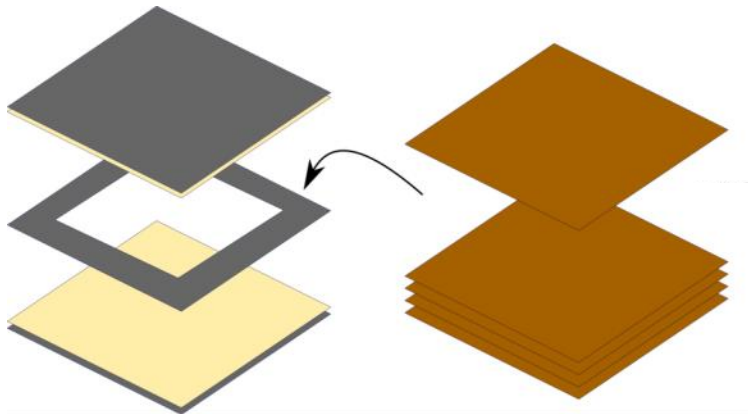


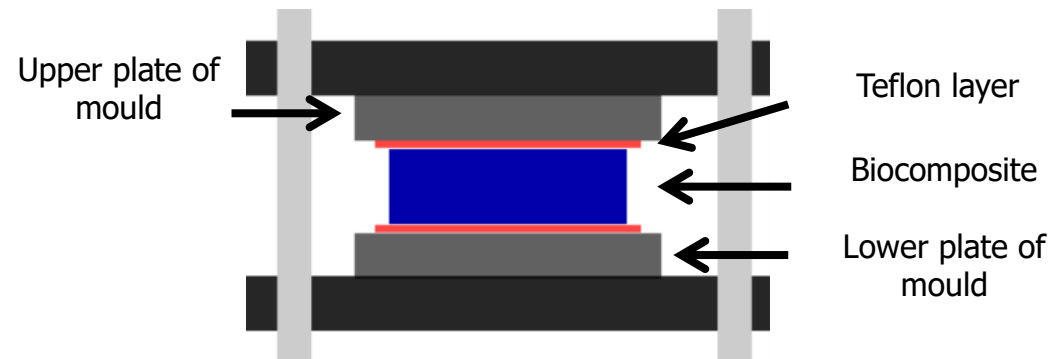
Figure 12: Commingled weave of flax with thermoplastic matrix (left) - (Source: Groupe Depestele); Thermoplastic prepreg of flax weave with powder (right) - (Source: Dehondt Groupe).

Zhang and Miao, Composites Science and Technology 70 (2010) 130–135

1. Staking of the prepregs fabrics



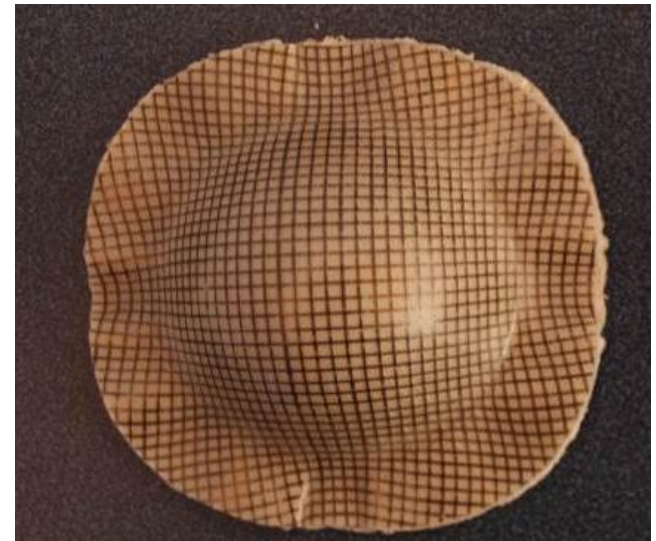
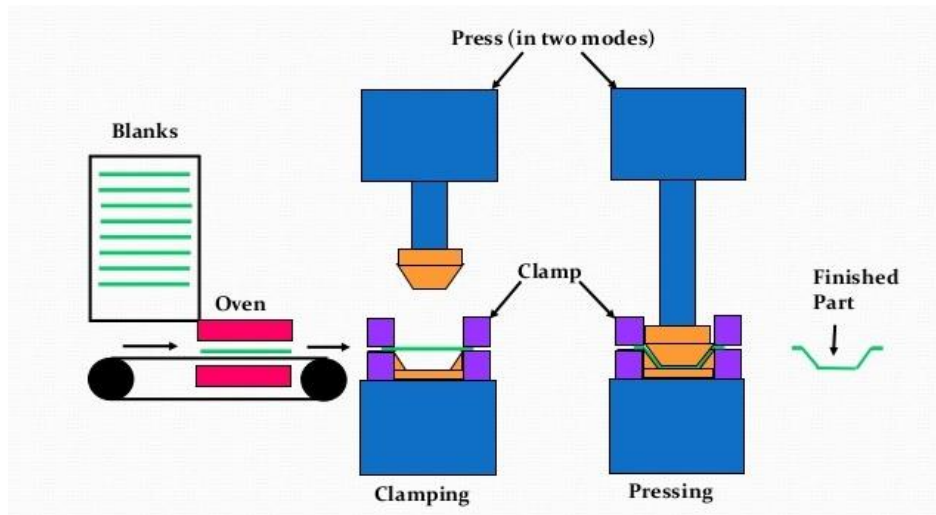
2. Thermocompression



Thermoplastics biocomposites

C. Thermoplastic prepregs

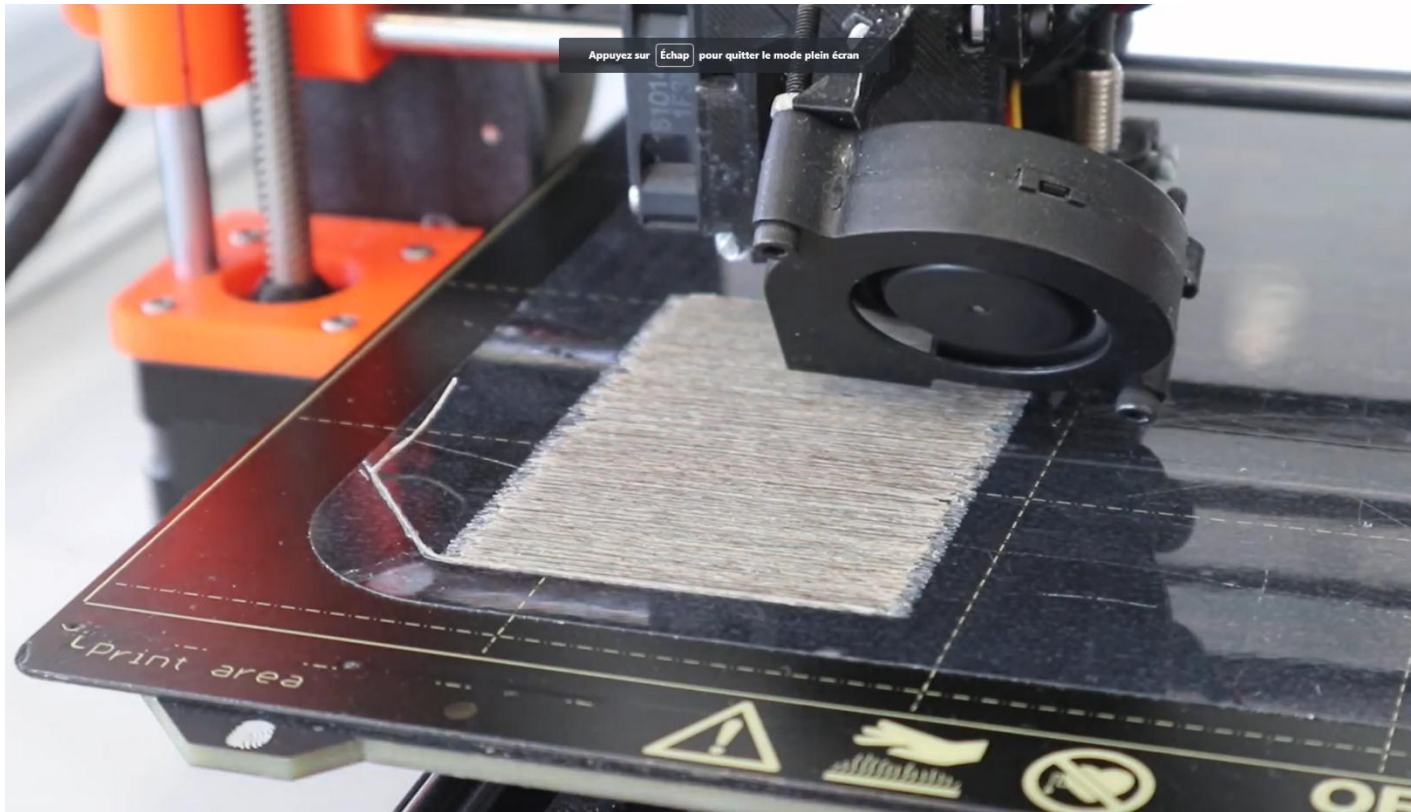
- Possibility to obtain complex shapes by thermoforming



Bamboo / PLA (Nurul Fazitaa, Materials, 2016)

Thermoplastics biocomposites

D. Emerging process : 3D printing of continuous flax / thermoplastic yarns



CORIOLIS
Coriolis Composites: The
reference in Automated
Fiber Placement ([coriolis-
composites.com](http://coriolis-composites.com))

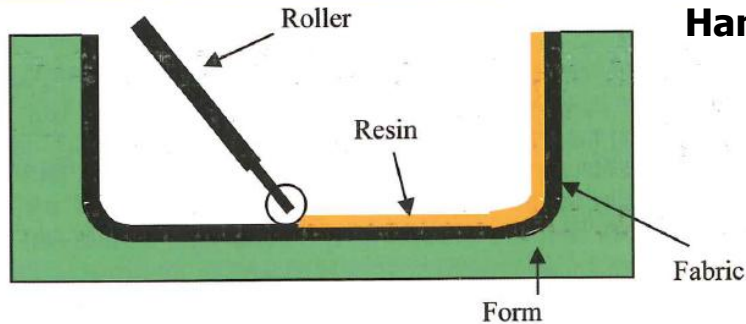
3D and 4D printing of continuous flax fibre Biocomposites (Le Duigou, UBS Lorient, France)

https://www.youtube.com/watch?v=PvGQ_5oCBi8

Thermosets biocomposites

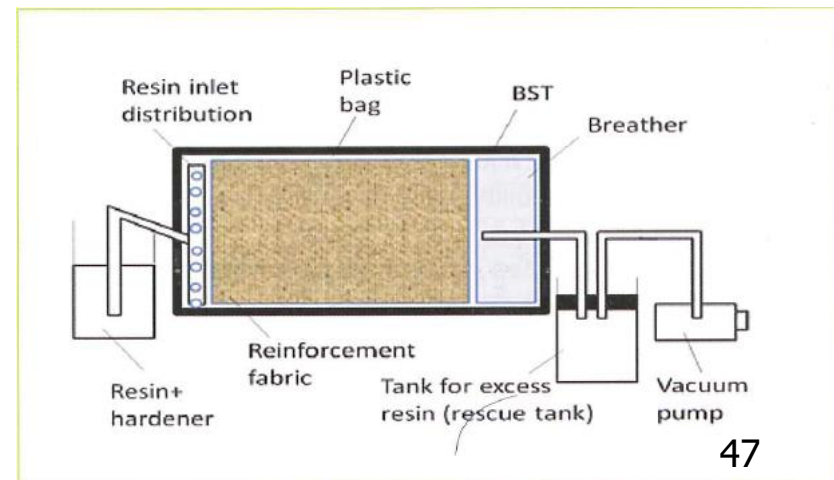
A. Dry fabrics

Hand lay-up



- Impregnation of dry fabrics with thermosets resin by hand lay-up or infusion
- Particularly adapted for big parts (boats)
- Other processes
 - RTM (resin transfert moulding)
 - SMC & BMC (sheet & bulk moulding compound)

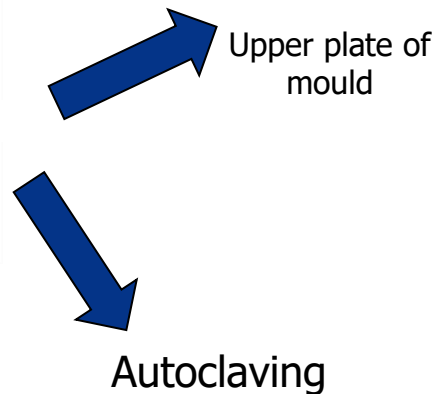
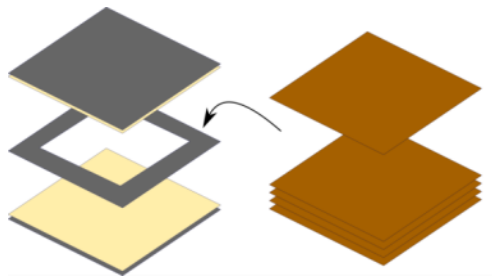
Infusion



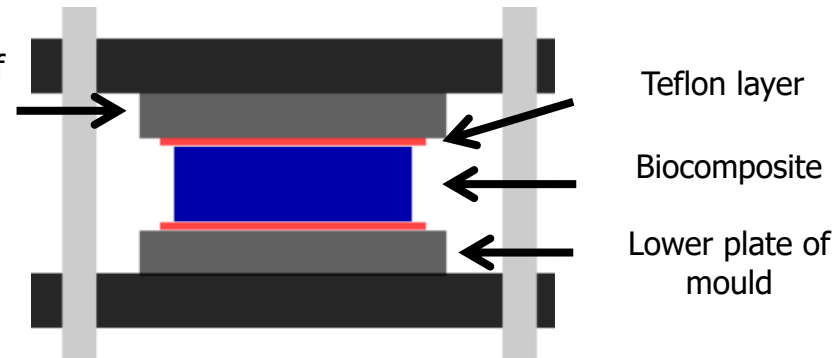
Thermosets biocomposites

B. Thermosets preregs

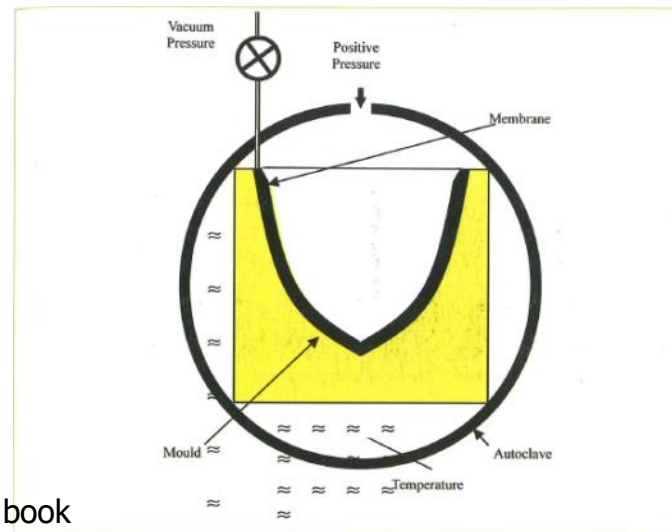
1. Staking of the preregs fabrics



Thermocompression

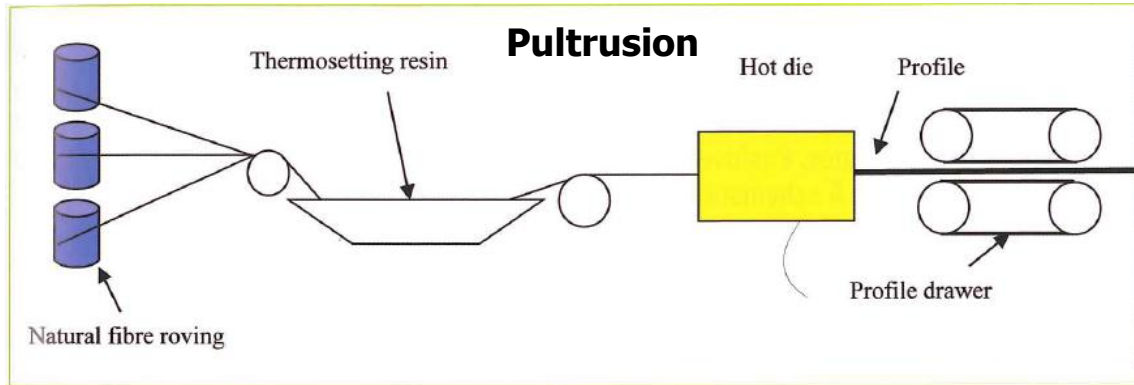


Autoclaving

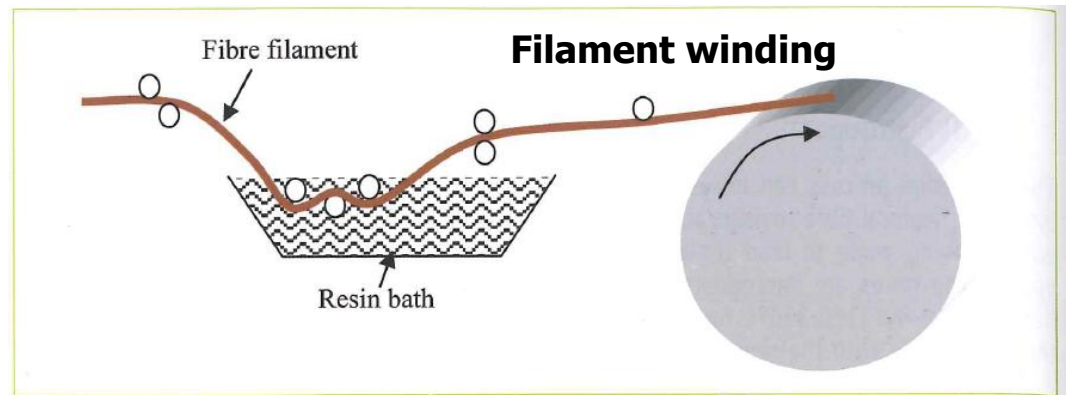


Thermosets biocomposites

C. Roving



- Continuous process for pultruded profiles, containers



Développements autour de la modification du bois

➤ Destructuration and/or densification

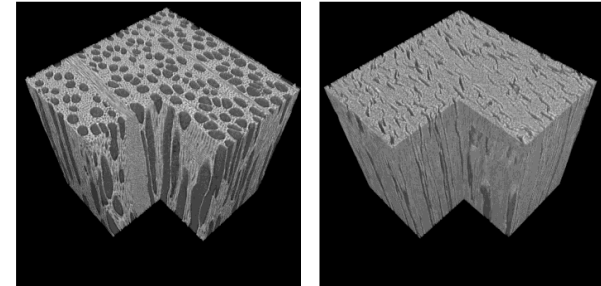


Chemistry in Pictures: Elastic wood

by Manny I. Fox Morone
SEPTEMBER 11, 2020



Credit: Lianshine Hu's research group



3D images (X-ray tomography) showing a typical cellular architecture of a beech wood sample before (upper micrograph) and after (lower micrograph) standard compression molding. (source 3SR lab)

nature

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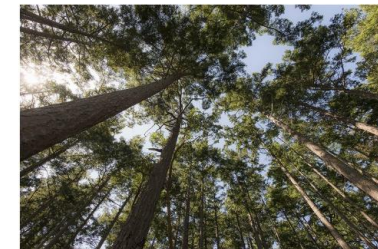
nature > news > article

NEWS • 07 FEBRUARY 2018

Crushed wood is stronger than steel

Compressing the material and removing some of its polymers can increase its strength tenfold.

Mark Zastrow



A new technique to densify natural wood could be used to strengthen cars and buildings. Credit: Jeff Mauritzen/NGC/Getty

RELATED ARTICLES

Turning wood into rub

SUBJECTS

Biomechanics Male

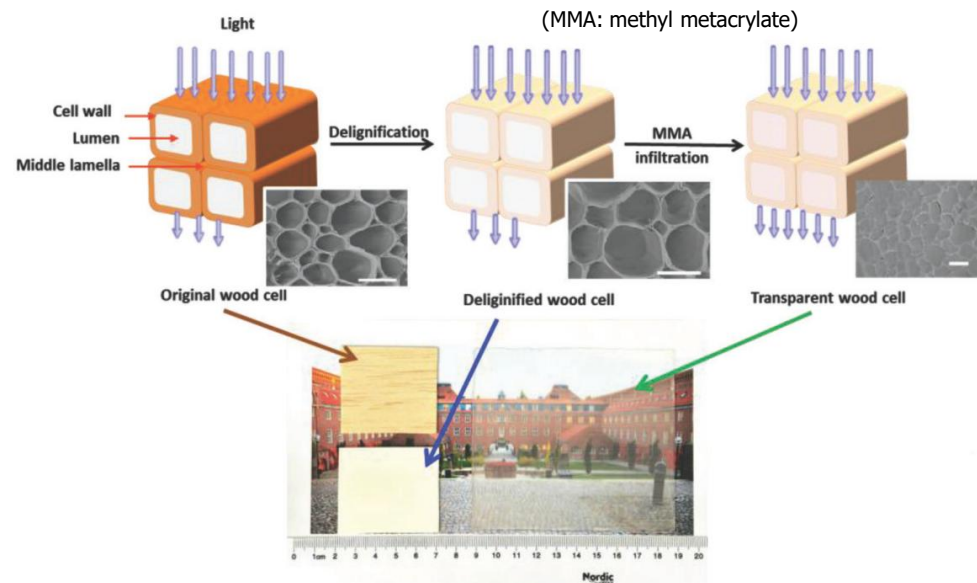


Piscines et Spa
Conception et ré
novation d'espac
s de détente

[Ballistic test of Super Wood - YouTube](#)

Alternative routes : modification of wood structure

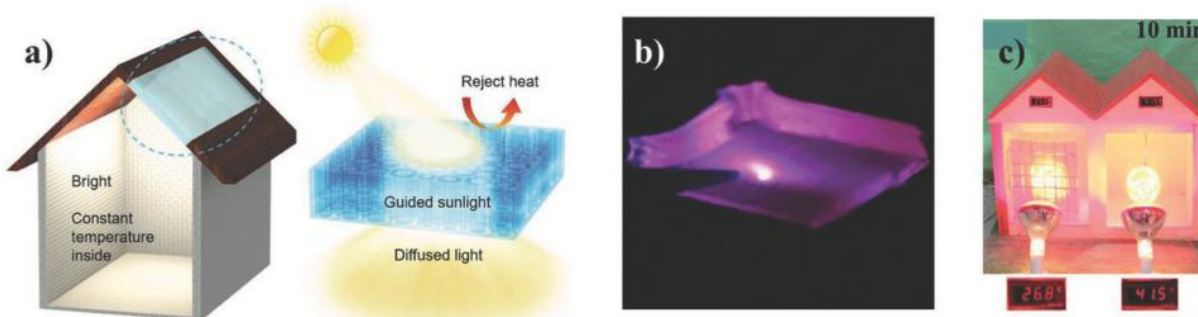
➤ Modification / Functionalization: transparent wood !



Engineered wood for :

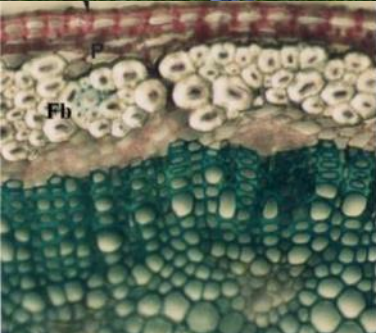
- *Light and thermal management,*
- *Nanofluidics,*
- *Water treatment,*
- *Batteries,*
- *Lightweight structural materials*

He, S et al. (2023). Engineered Wood: Sustainable Technologies and Applications. *Annual Review of Materials Research*, 53.



Summary

- Bio-based and biodegradable polymers
- From bioplastics to biocomposites
- Natural fibre structure, properties & processing
- **Biocomposites processing & properties**
- Market & applications



Biocomposites properties

Main influencing parameters ?



(Matrix properties)

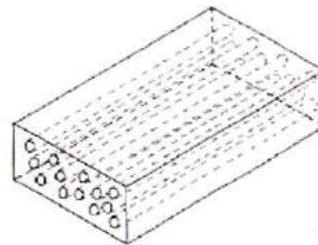


Fibre orientation

Fibre type and
properties

Fibre length

Mechanical performance
of composites

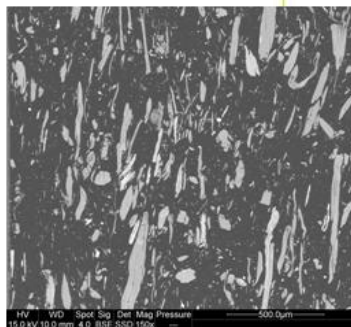
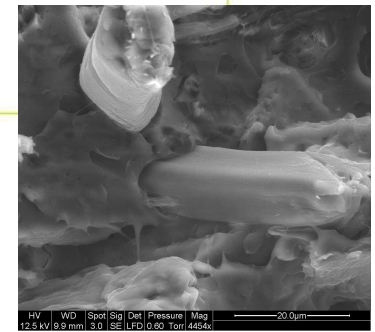
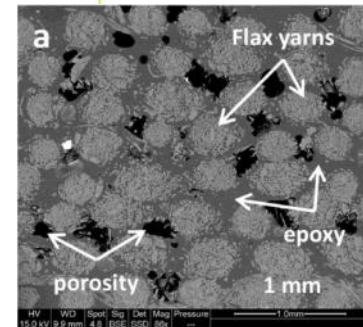


Porosity

Fibre content

Fibre/matrix interface
properties

Relative humidity



Fibre
impregnation
and packing



Biocomposites properties

B. Case study : various wood species and processing

ADEME



Agence de l'Environnement
et de la Maîtrise de l'Energie

COLLECTED BRANCHES OF DIFFERENT TREE SPECIES IN AGROFORESTRY SITES

Young poplar



Oak



Chestnut



Old poplar



Walnut



FRACTIONATION AND CALIBRATION: WOOD FRACTIONS AT DIFFERENT GRANULOMETRY

250 – 500 μm

500 – 1000 μm

1000 – 2000 μm



Commercial Reference:
Spruce for WPCs



Cellulose (%)	29.5 $\pm$ 0.6	25.5 $\pm$ 0.7	38.2 $\pm$ 0.6	28.7 $\pm$ 1.6	26.1 $\pm$ 0.3	49.7 $\pm$ 0.0
Hemicellulose (%)	42.1 $\pm$ 0.6	43.7 $\pm$ 0.7	39.1 $\pm$ 0.6	42.2 $\pm$ 1.6	45.5 $\pm$ 0.3	29.7 $\pm$ 0.0
Lignin (Klason) (%)	28.5 $\pm$ 0.6	26.0 $\pm$ 0.3	26.9 $\pm$ 1.1	29.0 $\pm$ 0.1	27.1 $\pm$ 1.0	27.4 $\pm$ 0.1
Extractives (%)	1.76	2.99	2.29	1.76	3.02	1.99

TWIN-SCREW EXTRUSION

PP 65%_w / PP-g-MA 5%_w / wood fillers 30%_w

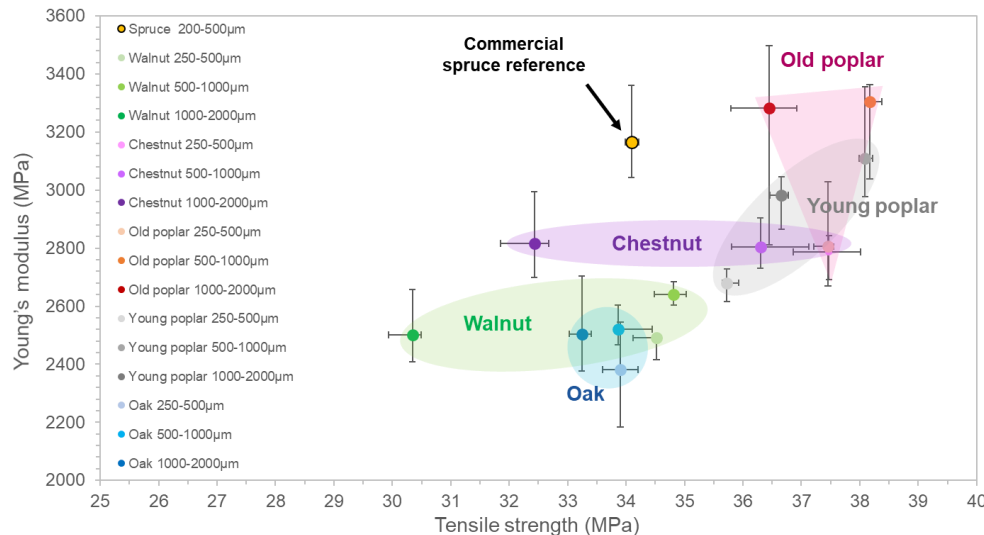
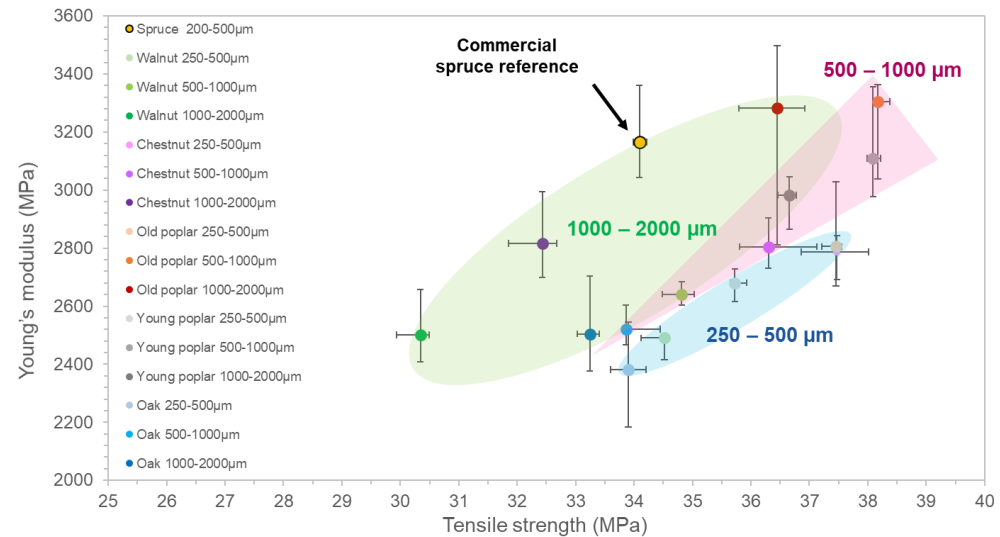
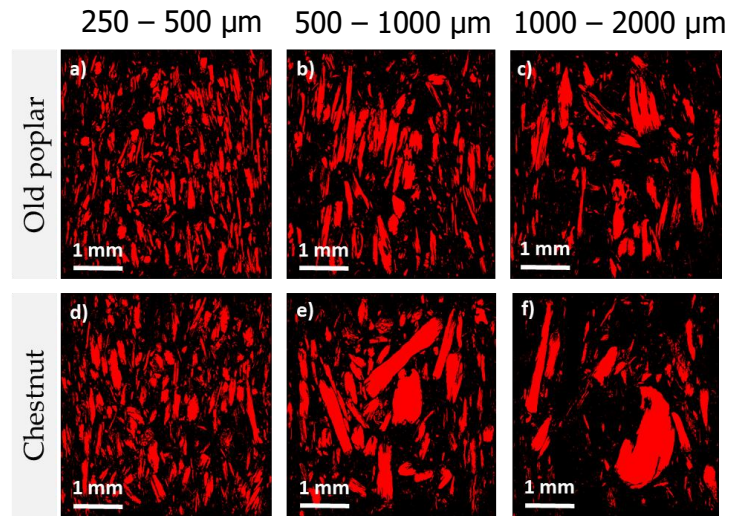


INJECTION MOLDING



Biocomposites properties

B. Case study : various wood species and processing



- **Results:** Microstructure and resulting **mechanical behaviour** of the composites are **highly species and granulometry dependant**, up to 40% variation in stiffness and strength !

Biocomposites properties

A. Effect of fibre properties : different sorghum genotypes

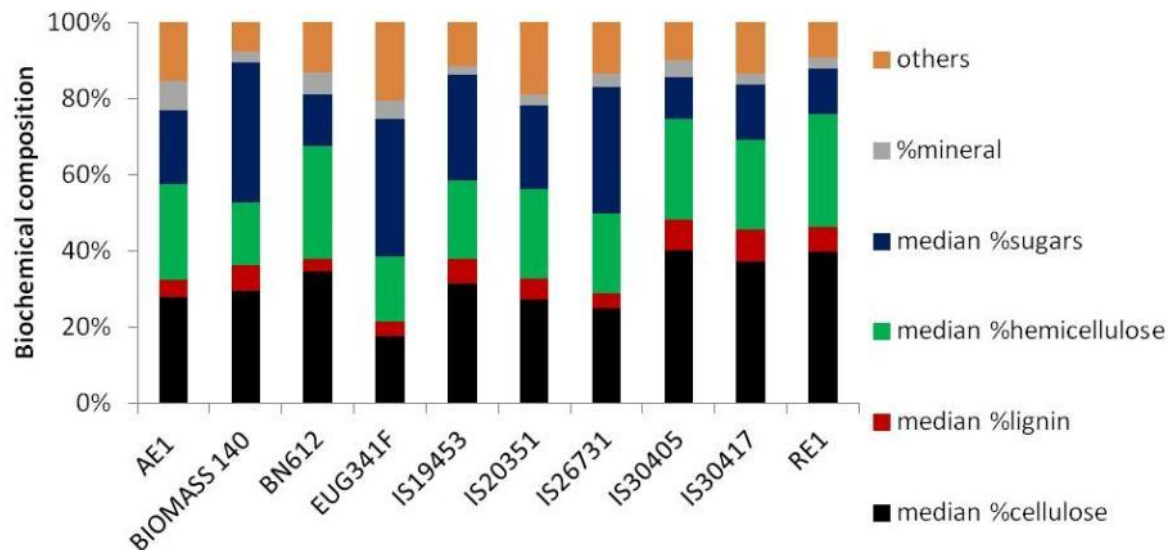
“Biosorg” project (2014-2017)

L. Soccalingame, N. Le Moigne, S. Corn, D. Pot

- Study of various sorghum genotypes / phenotypes
- Identify the sorghum biological traits contributing to the performances of sorghum biocomposites



Biochemical composition of sorghum genotypes



Biocomposites properties

A. Effect of fibre properties : different sorghum genotypes

“Biosorg” project (2014-2017)

L. Soccalingame, N. Le Moigne, S. Corn, D. Pot

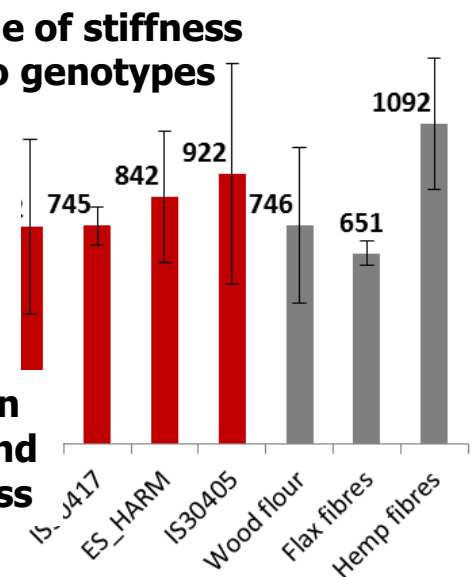
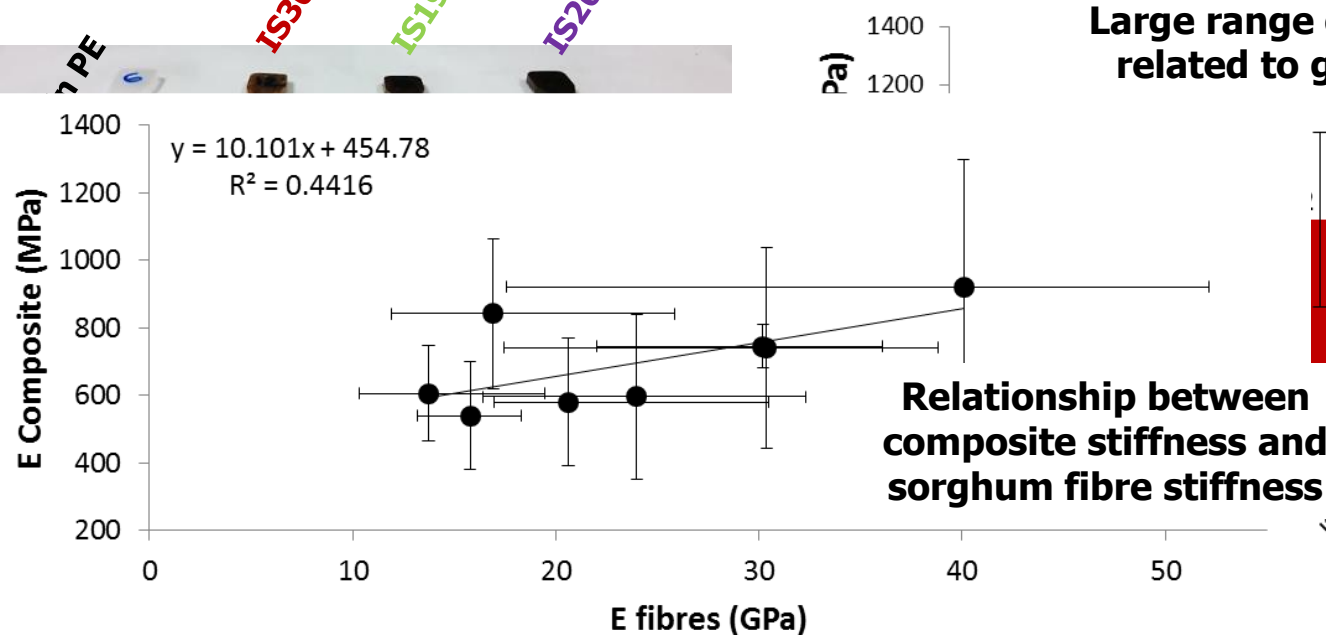
- Significant effect of sorghum genotypes / properties on composite physical properties

Colouring of sorghum biocomposites

PE / PE-g-MA / Sorghum
68.5 / 1.5 / 30



Mechanical properties of sorghum biocomposites



Biocomposites properties

Conclusions on the effects of fibre properties and dimensions

Species, genotypes, internodes...

(Composition and structure)



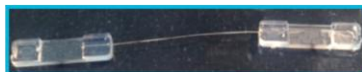
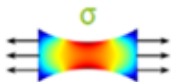
Outcomes :

- More virtuous cultivation routes
- Promote biodiversity
- Preserving ecosystems



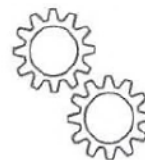
Mechanical properties

(modulus and strength)



Processing

(Fragmentation mechanisms and fibres/fragments dimensions)



Biocomposites properties

Main influencing parameters ?



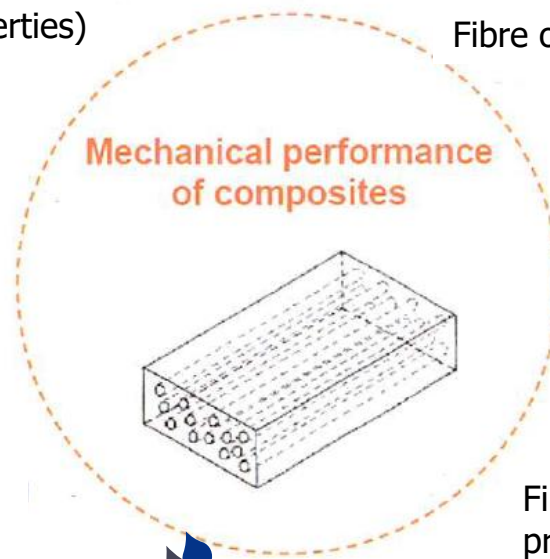
(Matrix properties)



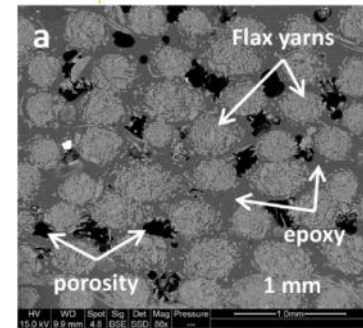
Fibre orientation



Fibre type and properties

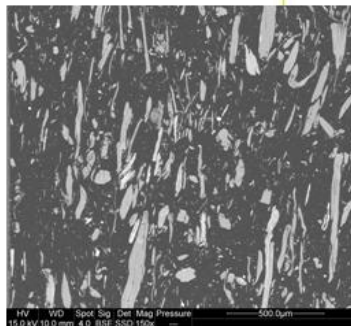


Porosity



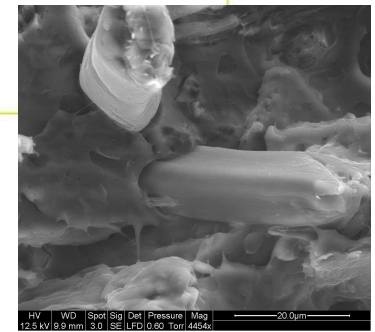
Fibre content

Fibre length



Fibre impregnation and packing

Fibre/matrix interface properties

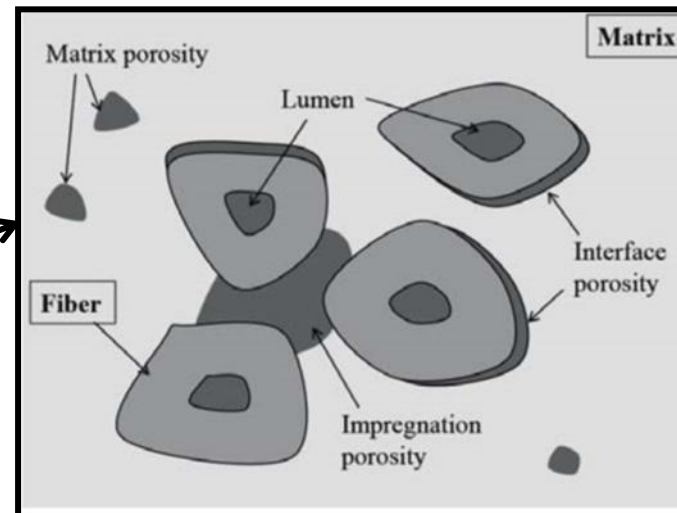
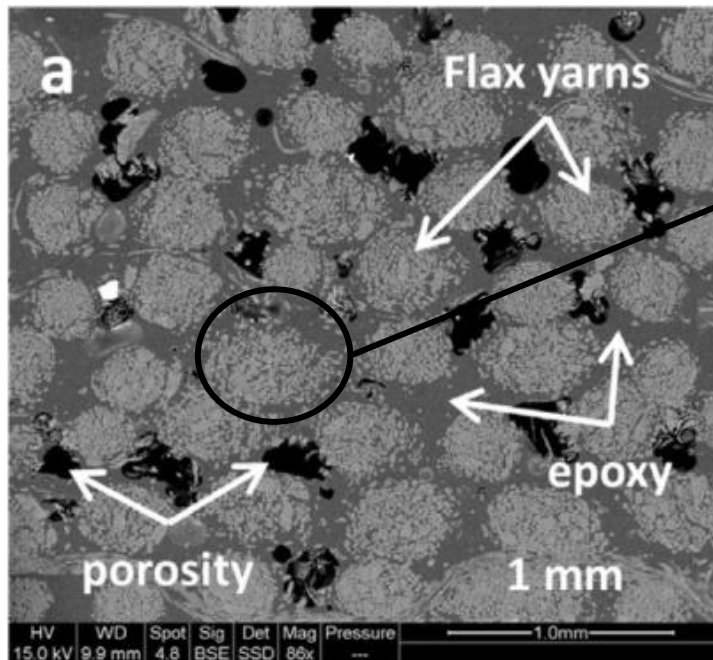


Relative humidity

Biocomposites properties

C. Porosity : definitions

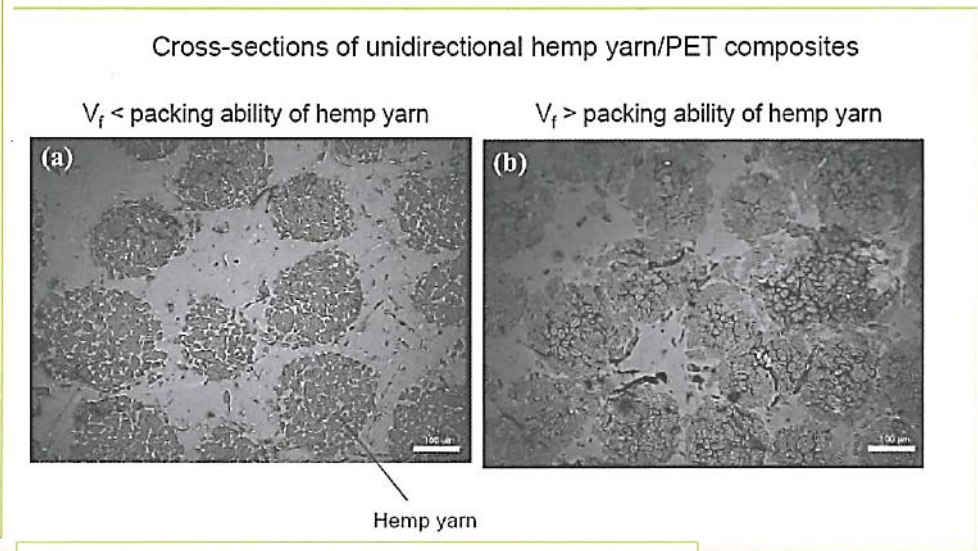
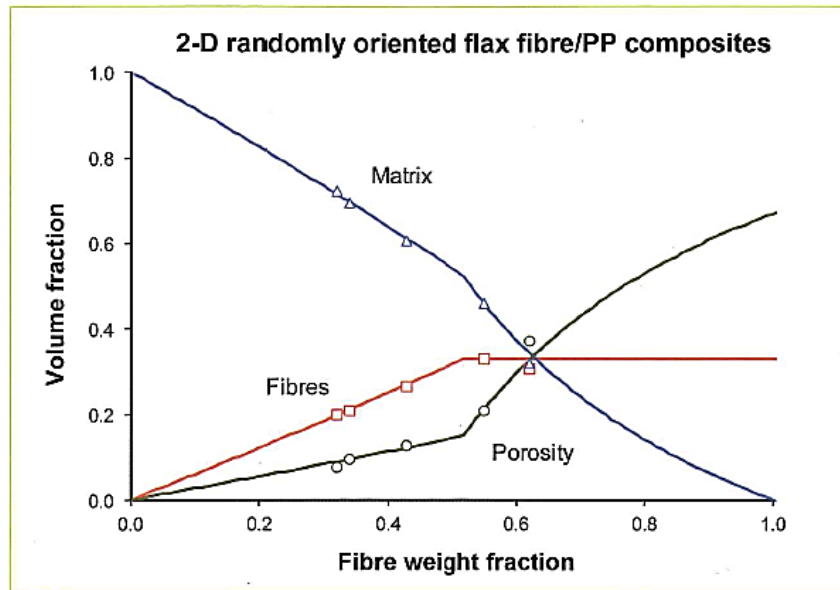
- Different types of porosity : from micro- to macro-porosities
 - Intrinsic porosity : lumen
 - Interface porosity : poor fibre / matrix interface
 - Impregnation porosity : high viscosity matrix and poor wettability
 - Matrix porosity : degassing



Madsen et al., 2007, Composites Science and Technology, 67

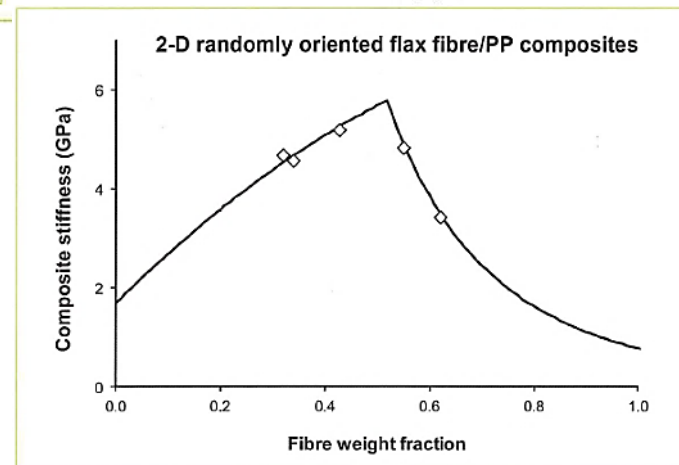
Biocomposites properties

C. Porosity : relation with fibre volume fraction and packing



If $V_f > \text{packing ability of fibres}$:

- Increasing porosity
- Decreased stiffness of composites



Biocomposites properties

C. Porosity : role of processing temperature and pressure

- Case study on thermocompression of flax/PP commingled fabrics

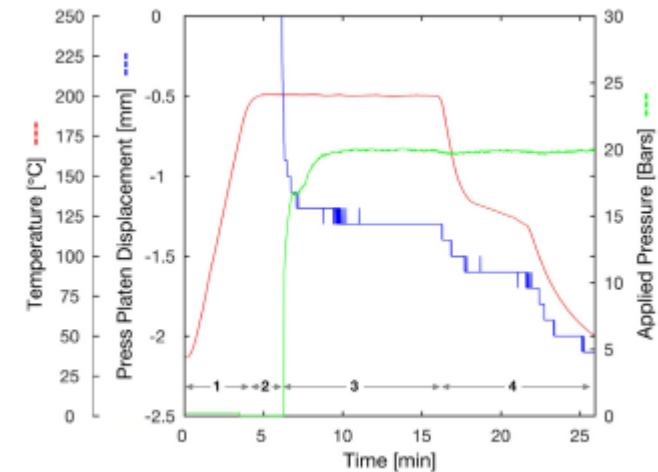
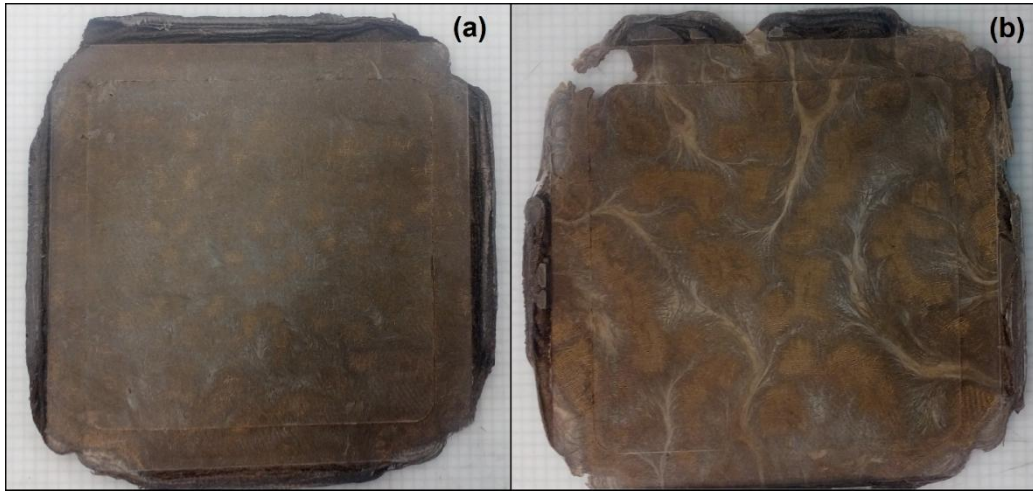


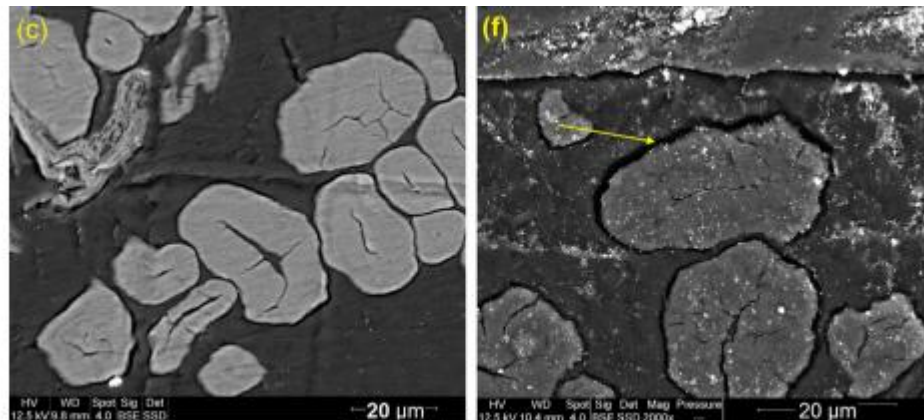
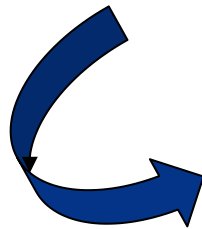
Fig. 1. (a) Fast induction-heated compression moulding press, (b) Close view of flax/PP commingled fabric, (c) 8 plies fabric layup and (d) Manufactured composite laminate.

Biocomposites properties

C. Porosity : role of processing temperature and pressure



Composite plates manufactured at (a) 240 C at 10 minutes and (b) 260 C at 5 minutes



Biocomposites properties

C. Porosity : role of processing temperature and pressure

➤ Effect on mechanical properties : large decrease of strength related to time / T°C exposure

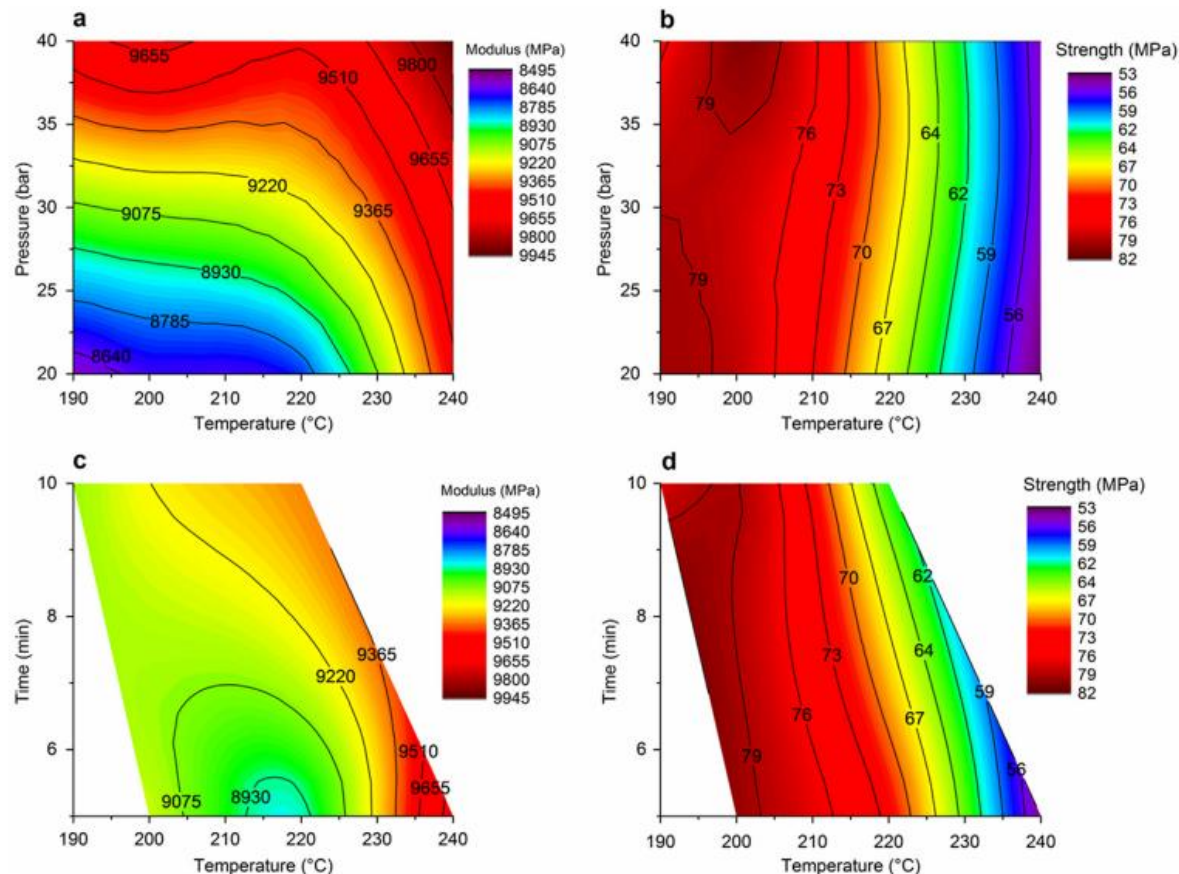


Fig. 11. (a, b) Effect of temperature and pressure and (c, d) effect of temperature and consolidation time on median modulus and strength of flax/PP biocomposites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Biocomposites properties

Main influencing parameters ?



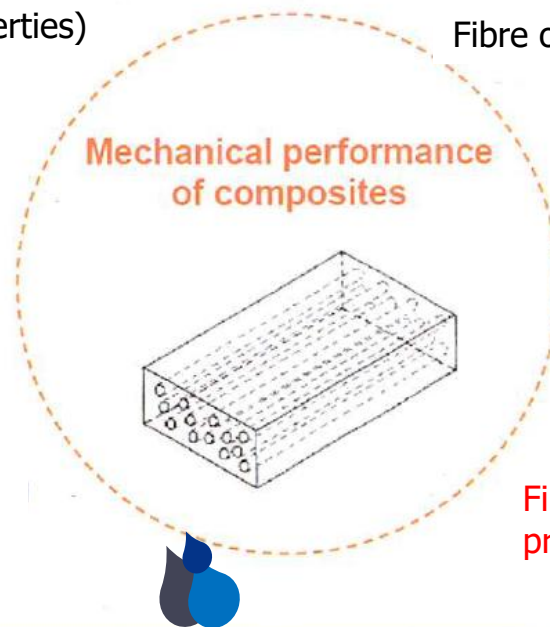
(Matrix properties)



Fibre orientation



Fibre type and properties



Mechanical performance of composites

Porosity

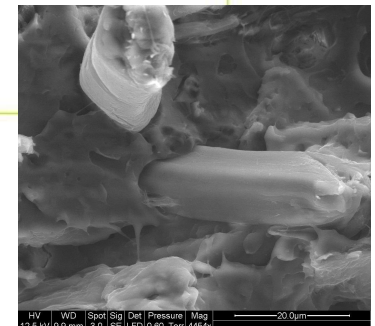
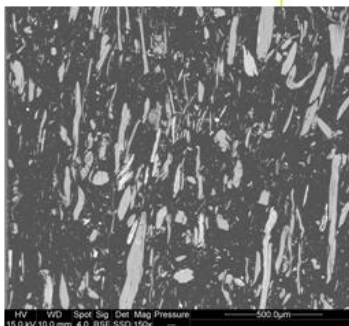
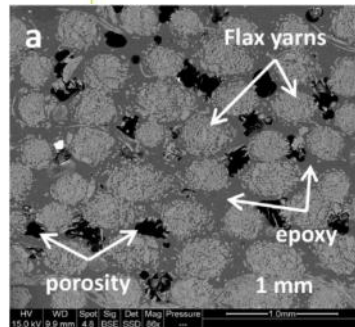
Fibre content

Fibre/matrix interface properties

Relative humidity

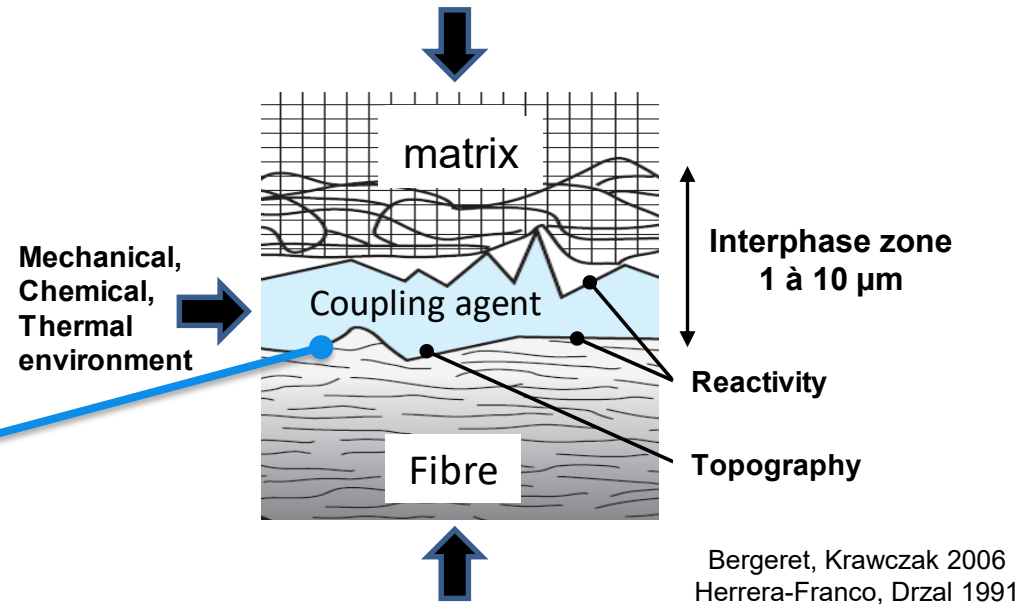
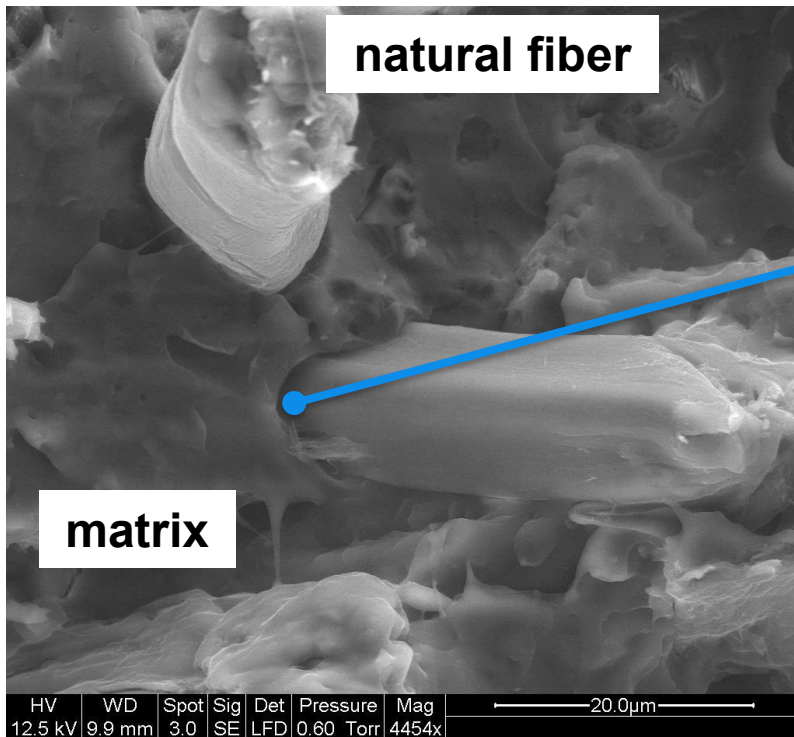
Fibre length

Fibre packing ability



Biocomposites properties

D. Role of the interface



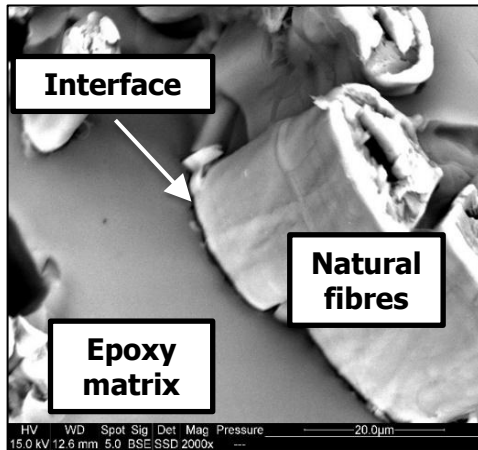
Better interfacial adhesion will:

- Ensure the load transfer from matrix to fibers
- Protect the composite towards ageing (humidity)

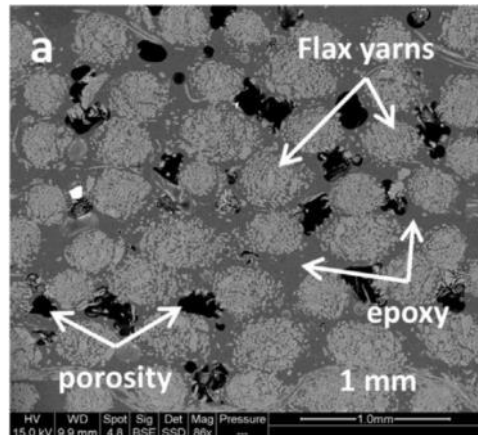
Biocomposites properties

D. Interface : modification strategies

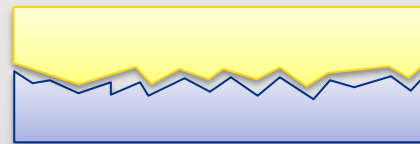
- Interaction fibre / matrix



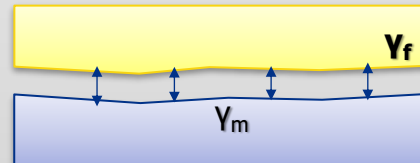
- Improving fibre dispersion



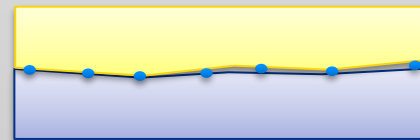
Interfacial adhesion governed by :



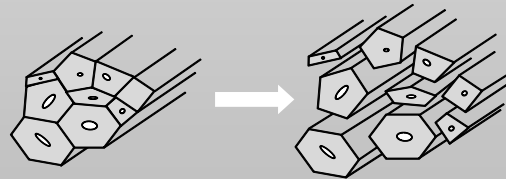
Roughness



Surface tension



Physico-chemical interactions

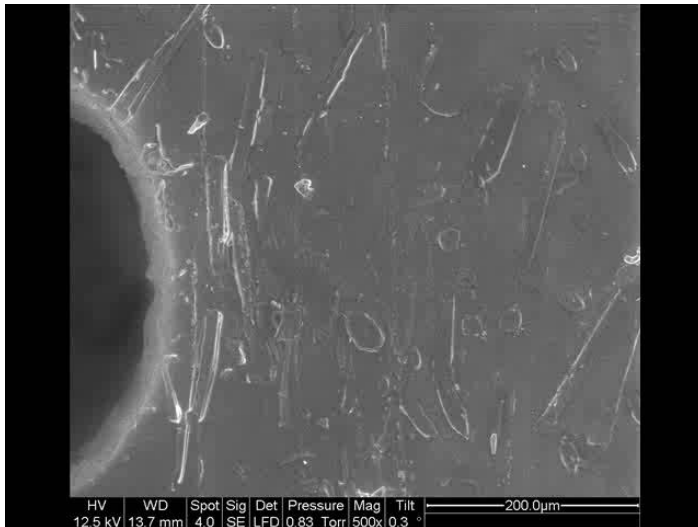


Specific surface

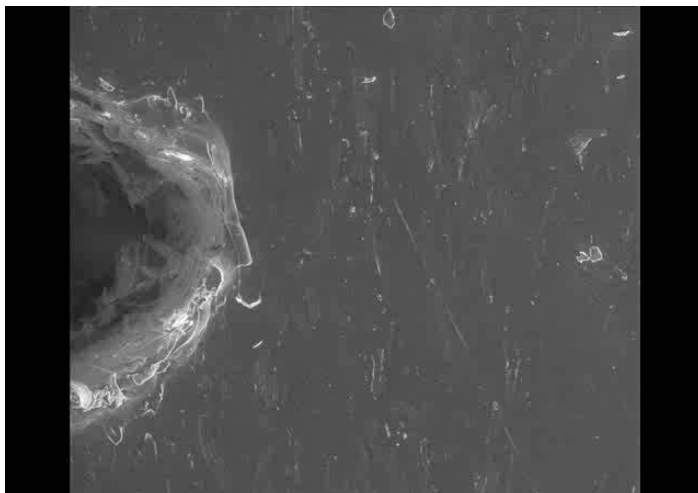
Biocomposites properties

D. e.g. silane treatment on PLA / flax composite

Non-treated fibres



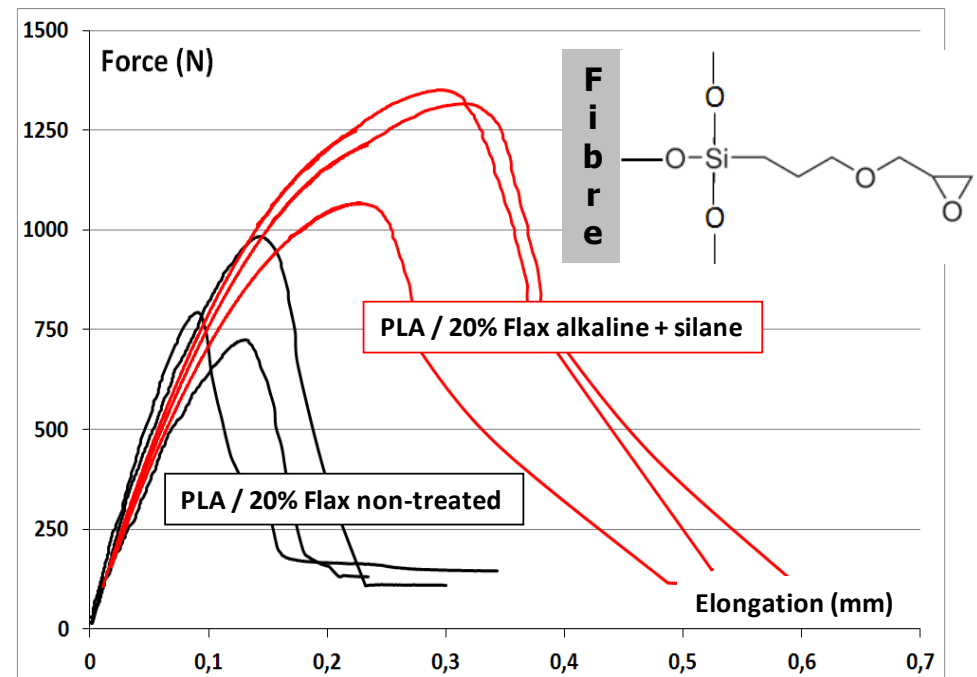
alkaline + silane fibres



In-situ tensile test
0.1 mm/min



➤ **Adhesive interfacial failure:** debonding of the fibres and clean break of the matrix



➤ **Cohesive interfacial failure :** tearing of the matrix and breaking of the fibres bonded to the matrix

Biocomposites properties

D. Effect of various treatments on biocomposites performances

- Limited effect of fibre & matrix treatments on modulus and strength

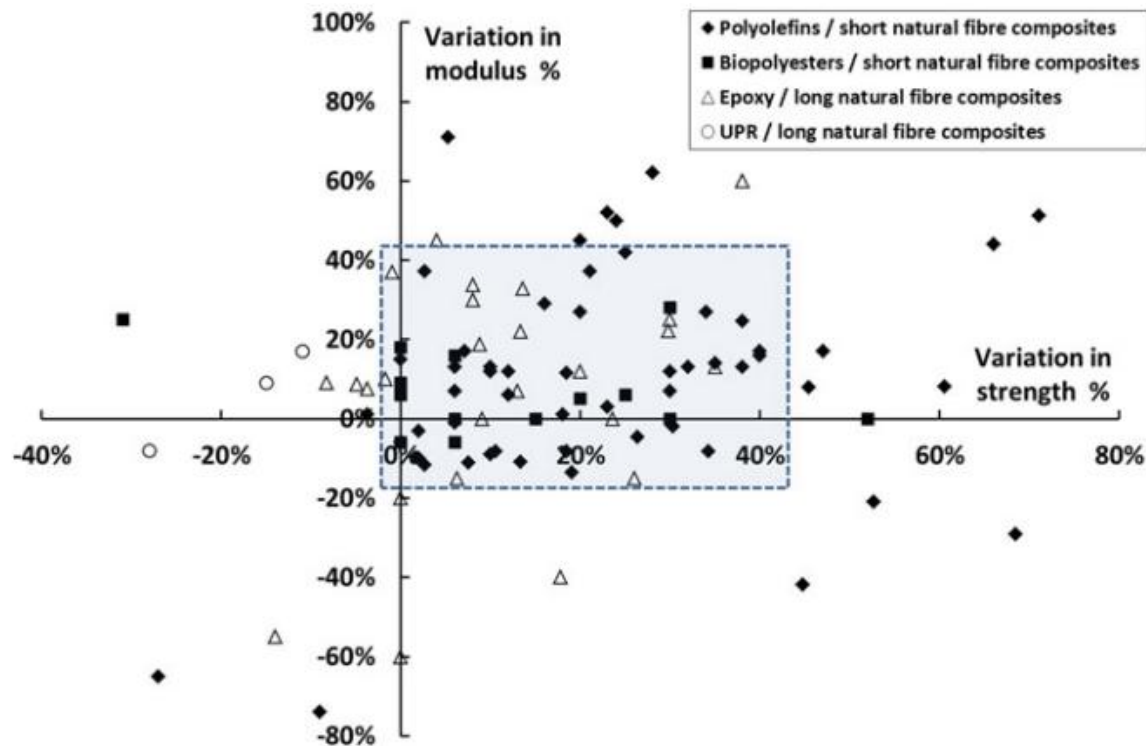


Fig. 3.8 Ashby plot—variation in modulus versus variation in strength of natural fibre reinforced composites consecutive to pre-treatments and/or functionalization of natural fibres. Non-exhaustive set of data taken from literature for polyolefins and biopolyesters/short fibre composites (tensile properties) and epoxy and unsaturated polyester (UPR) resins/long fibre composites (flexural or tensile properties)

Biocomposites properties

D. Towards hybrid and hierarchical interphases

- What can be learned from Nature ?
- Hierarchical organization with nanoscale structuration at the interphase greatly enhance strength and toughness of biological systems : limiting stress concentration and crack propagation

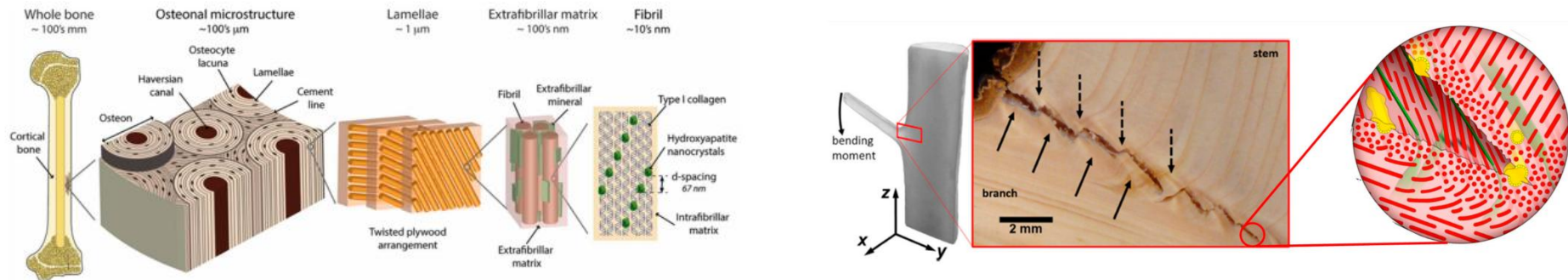
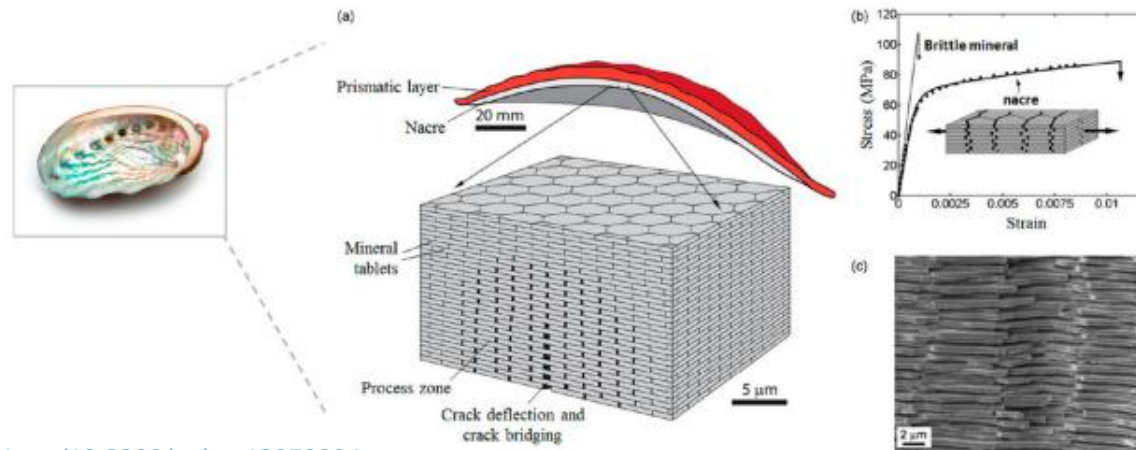


Figure 1. Hierarchical structure of human cortical bone with the presence of hydroxyapatite mineral nanocrystals (reprinted with permission from Zimmermann et al., 2016 [40]).



Biocomposites properties

D. Towards hybrid and hierarchical interphases

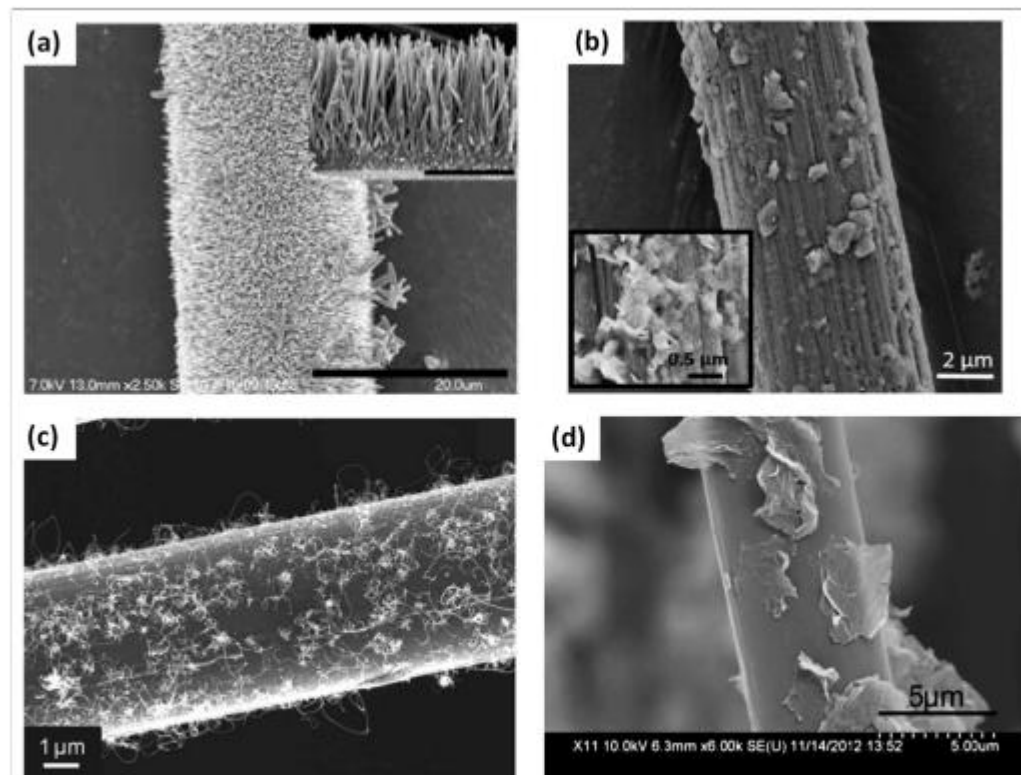


Figure 5. SEM images of hierarchical synthetic fibres (a) aligned ZnO nanowires coated and grown on aramid fibres (functionalized with carboxylic acid groups); (b) Si-nanoclays (nanoclays functionalized with APTES) grafted on N-CF (carbon fibre modified with GTMAC); (c) CNTs grown on oxidized IM7 carbon fibres using CVD method; (d) graphene nanosheets deposited on carbon fibre at a content of 1 wt% (reprinted with permission from Ehlert and Sodano 2009 [56], Zabihi et al., 2017 [50], Qian et al., 2010 [57] and Chen et al., 2015 [21]).

Biocomposites properties

D. Towards hybrid and hierarchical interphases

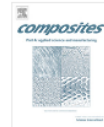
Composites: Part A 43 (2012) 2065–2074



Contents lists available at SciVerse ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa



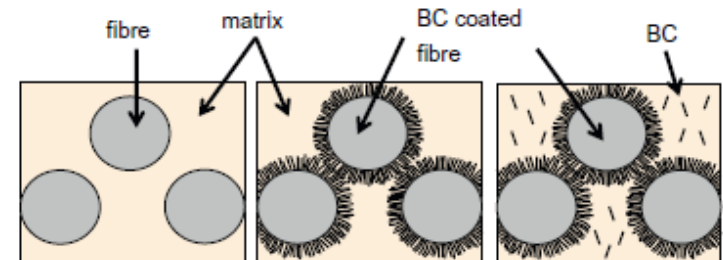
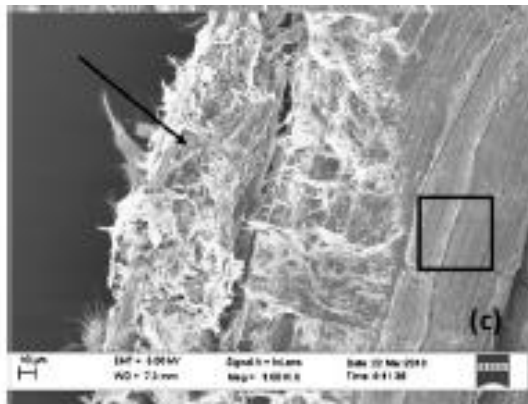
Short sisal fibre reinforced bacterial cellulose polylactide nanocomposites using hairy sisal fibres as reinforcement

Koon-Yang Lee, Puja Bharadia, Jonny J. Blaker, Alexander Bismarck*

Polymer and Composite Engineering (PoCE) Group, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

Goal:

“Hairy” or “Dense” Bacterial Cellulose (BC) coated sisal fibres (slurry dipping process)

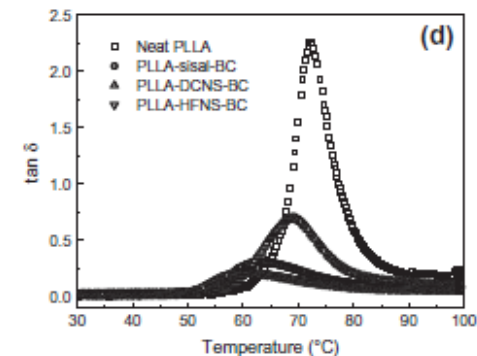


Results:

↗ Specific surface area of sisal fibres with “hairy” BC

Sample	BET surface area ($\text{m}^2 \text{g}^{-1}$)
Neat sisal fibres	0.10 ± 0.01
DCNS fibres	0.77 ± 0.03
HNSF fibres	0.49 ± 0.03

↗ Tensile, flexural and visco-elastic properties of **PLLA nanocomposites** over neat PLLA



Biocomposites properties

Main influencing parameters ?



(Matrix properties)



Fibre orientation

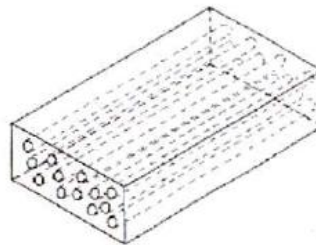
Fibre type and properties

Mechanical performance of composites

Porosity

Fibre content

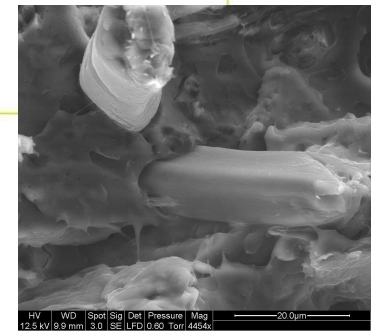
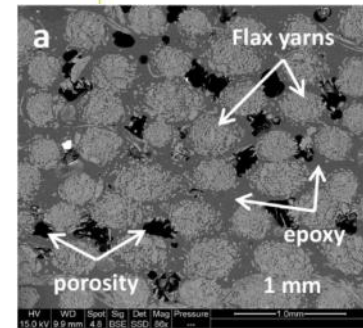
Fibre length



Fibre packing ability

Fibre/matrix interface properties

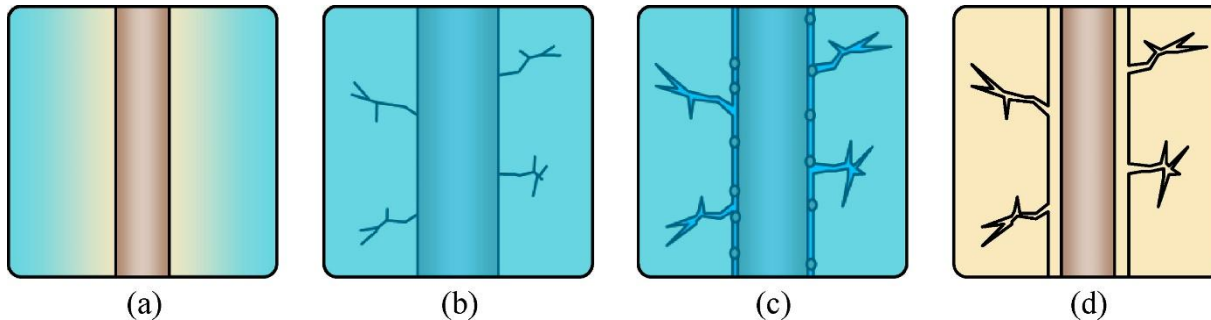
Relative humidity



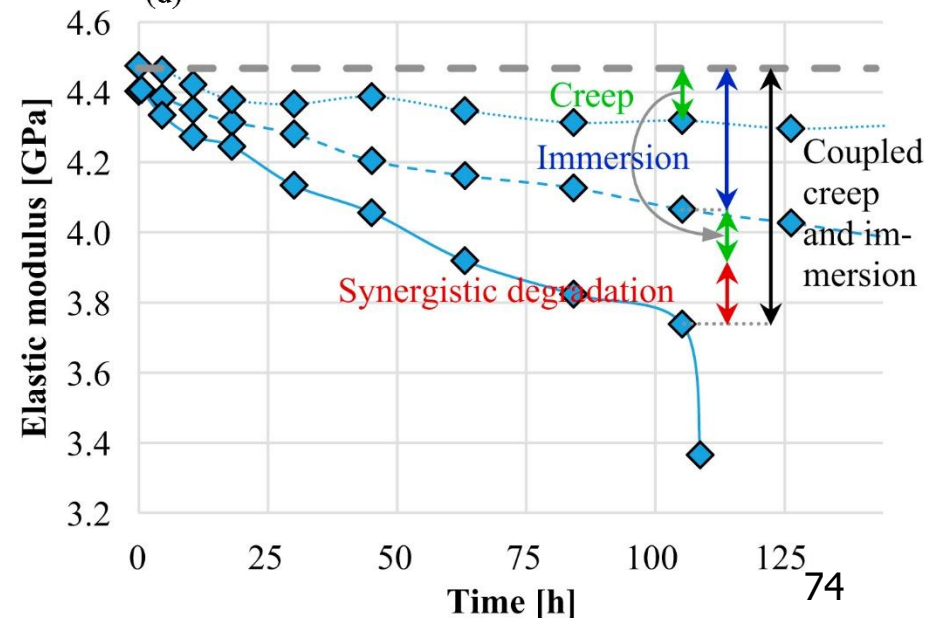
Biocomposites properties

E. Effect of relative humidity

➤ Moisture can cause swelling and loss of mechanical performances (plasticization, lower strength, local stress) and must be taken into account and predicted...



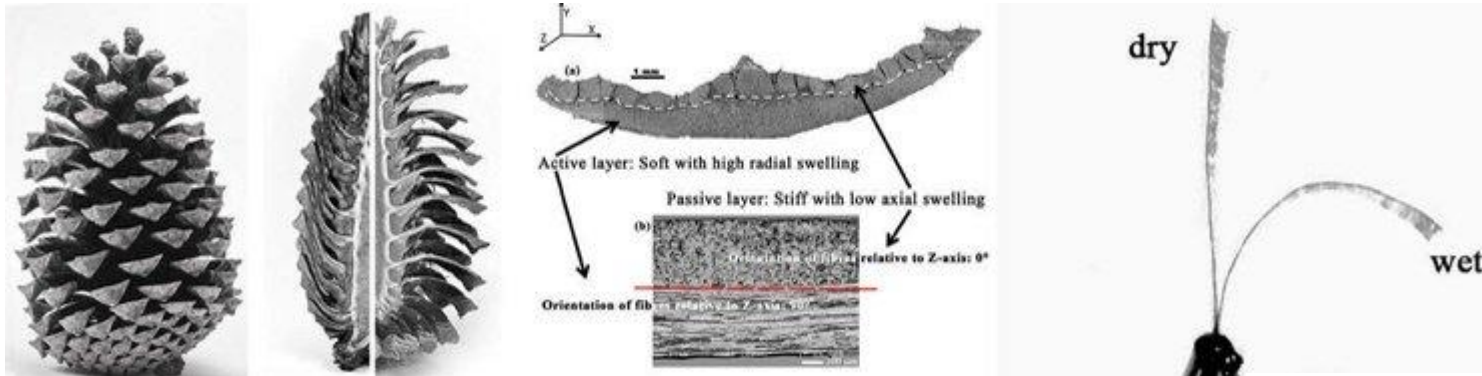
- local damages due to fibre swelling
 - Cracks and interfacial decohesion
- Synergistic degradation due to coupled creep and immersion



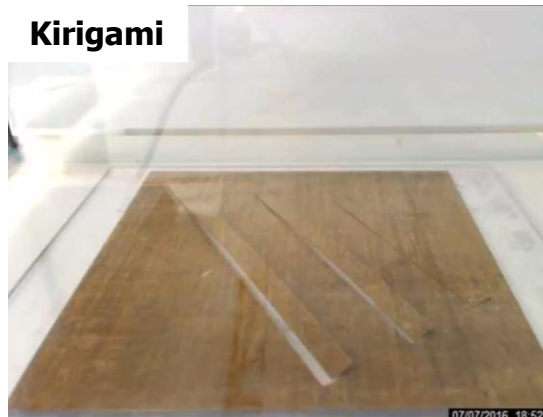
Biocomposites properties

E. Effect of relative humidity

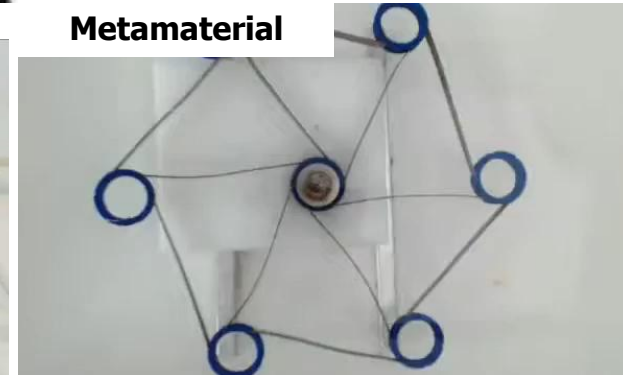
- Moisture can cause loss of mechanical performances (plasticization, lower strength) and must be taken into account and predicted...
- But it can also be an advantage !



Kirigami



Metamaterial



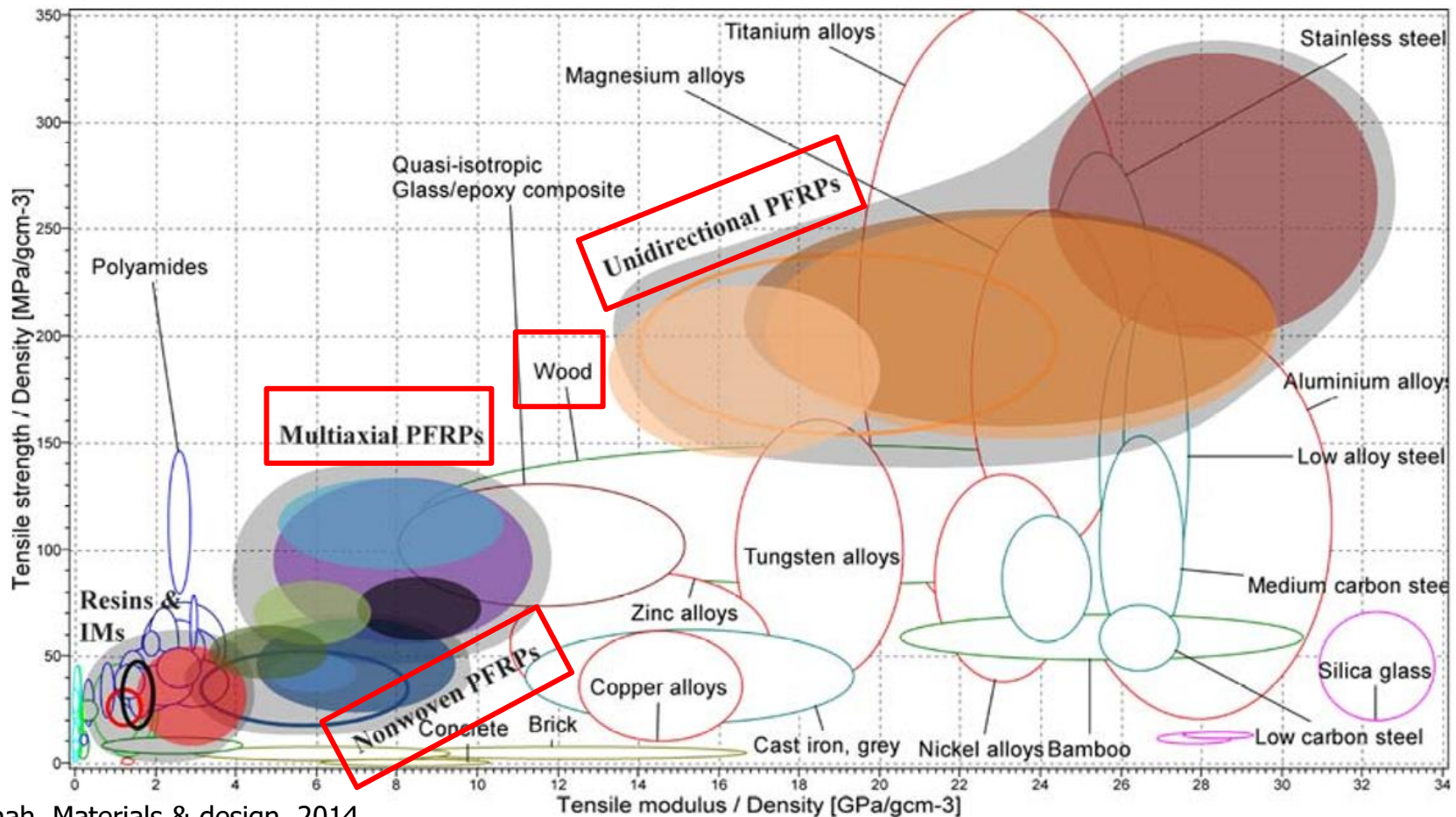
Le Duigou, Castro (2018) JEC Composites conference
Le Duigou, A., et al. (2017) *Smart Materials and Structures*,
26(12), 125009.
De kergariou et al. *Adv. Funct. Mater.*(2023) 33

<https://bionics-group.com/research/>
<https://www.youtube.com/@antoineleduigou2841>

Concluding remarks

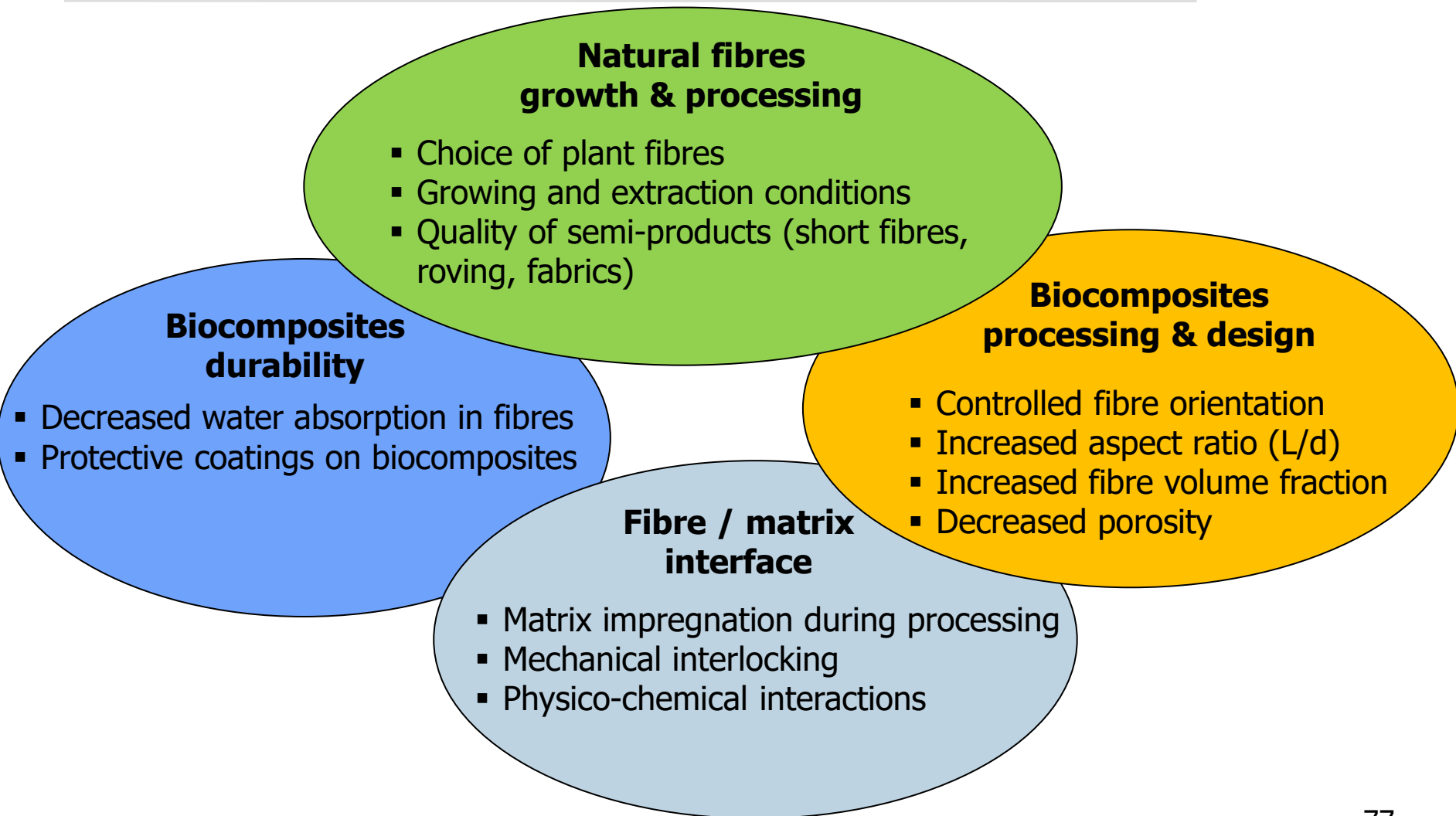
Biocomposites versus other engineering materials

- High tensile performances can be reached with biocomposites if the selection and manufacturing of natural fibres and their composites are controlled



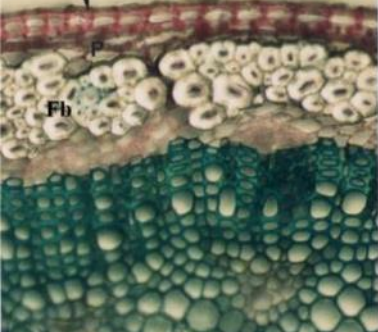
Concluding remarks

How to improve biocomposites performances ?





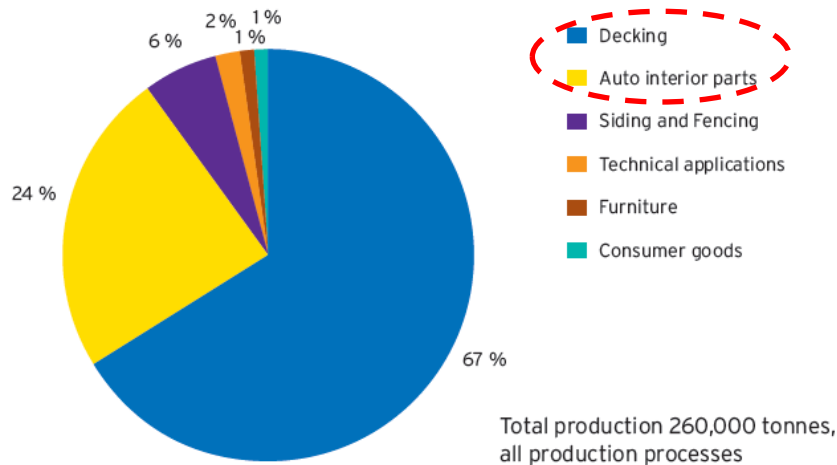
Summary

- 
- Bio-based and biodegradable polymers
 - From bioplastics to biocomposites
 - Natural fibre structure, properties & processing
 - Biocomposites processing & properties
 - **Market & applications**
- 
- 

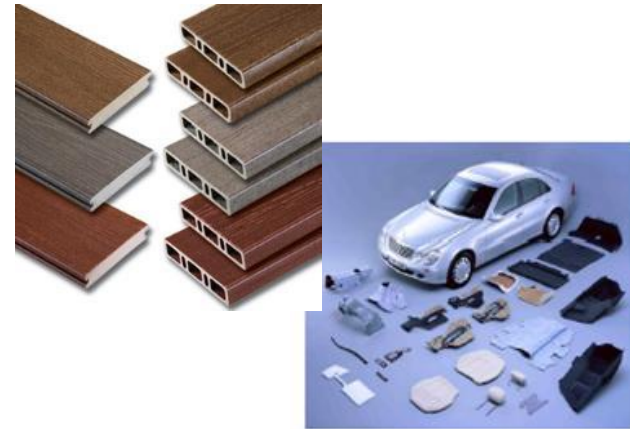


Market and application by sector and fibre type

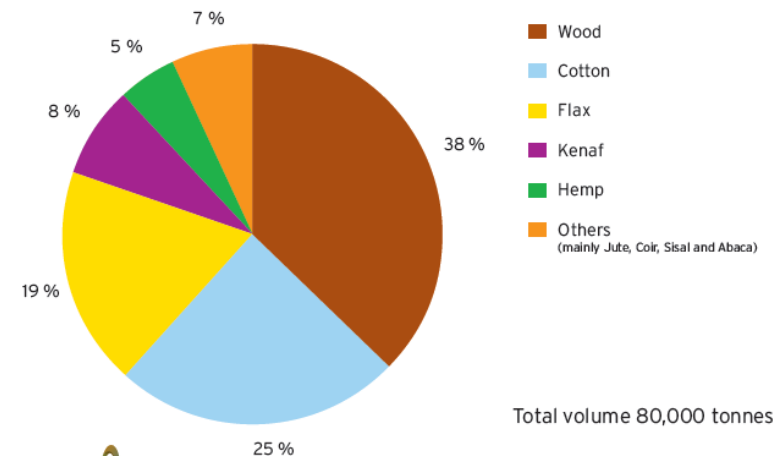
Application fields of wood-plastic composites in Europe in 2012



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Use of Wood and Natural Fibres for Composites in the European Automotive Industry 2012

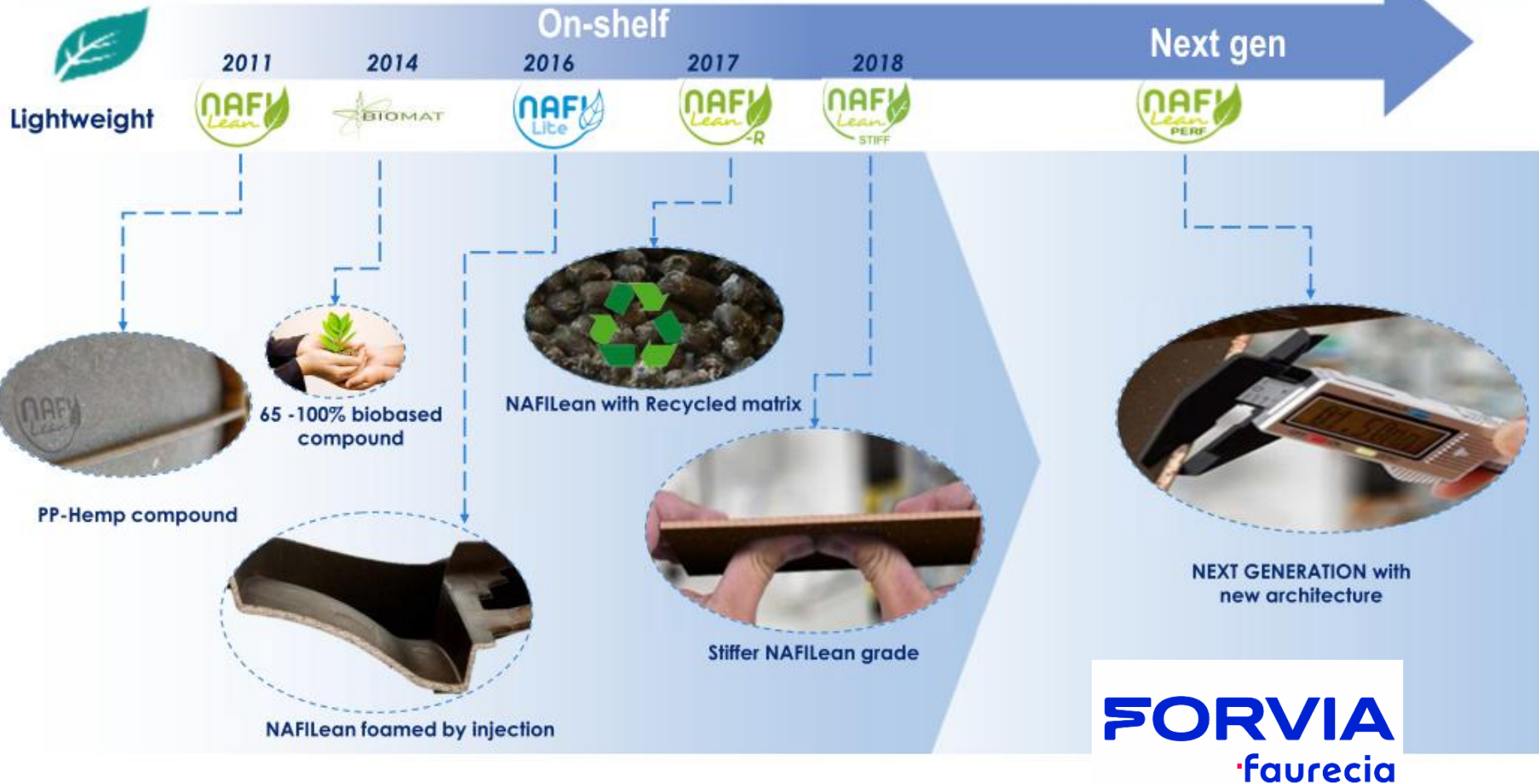


© nova-Institute.eu | ASTA EDER-Composites Consulting | 2014

Worldwide production in 2015 : 3.8 million tons

Automotive applications

NF compounds portfolio and innovation extract



Automotive applications

INTERNAL & PARTNERS

NAFILEan family on the road

22 programs in serial since 2013

LAND ROVER VELAR (GRAND EVOQUE)



Premium vehicle
SOP 2017

2.05kg /veh: Top rolls + Trims
685g weight saved (25%)
71% CO₂ reduction*

PEUGEOT 308



High volume production
SOP 2021

5,2kg /veh: IP structure
500g weight saved (11%)
56% CO₂ reduction*

RENAULT CLIO



IP Structural Duct



IP Instrument panel



IP Upper

New Renault Clio
SOP 2019

3,8kg /veh: IP Upper + structure + IP
Instrument panel
743g weight saved (16%)
31% CO₂ reduction*

NISSAN ARIYA



Premium vehicle
SOP 2021

2kg /veh: CC structure
250g weight saved (11%)
56% CO₂ reduction*

Automotive applications

Thermoplastic Reinforcement Materials

EcoTechnilin

Natur

FIBRIPLAST

NATURAL FIBRE/PP (NFPP) OR GLASS/PP (GFPP) NONWOVENS FOR USE IN THERMOCOMPRESSSION

AREAL WEIGHTS FROM 300 TO 2400 G/M²

FIBRES: FLAX, HEMP, KENAF, JUTE, GLASS,
PP, PET, PA...

MAIN ADVANTAGES :

- ✓ **LIGHTWEIGHT**
- ✓ **ACOUSTIC**
- ✓ **GOOD MECHANICAL PROPERTIES**
- ✓ **ONE-SHOT PROCESS TO FORM THE FINISHED PART**



GFPP



NFPP

Automotive applications

Applications in Automotive

EcoTechnilin

natup

Instrument panels



Headliners



Rear parcel Shelves



Door trims



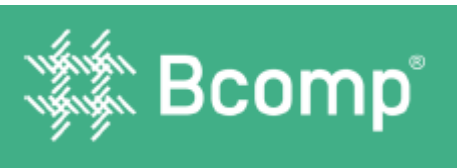
Trunk trims



A market reality



New developments



VALUE PROPOSITION

CO2 neutral reinforcement fibres
Natural liveliness and excellent
vibration damping

Up to 85% lower CO2 footprint
Improved safety

Up to 50% weight reduction
Up to 70% plastic reduction
Up to 60% lower CO₂ footprint
Multiple design options

Lightweight component design
Viable end-of-life solutions
Meet Fire Smoke and Toxicity (FST)
requirements

PRODUCTS

ampliTex™

ampliTex™
powerRibs™

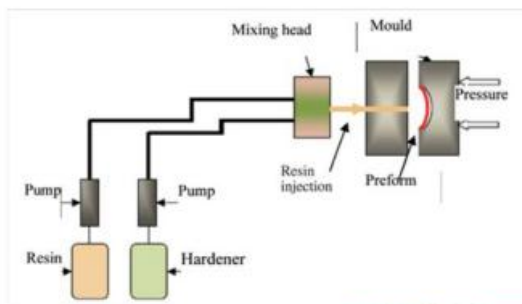
ampliTex™
ampliTex™-PP
powerRibs™-PP

ampliTex™-FR
powerRibs™
powerRibs™-PP



New developments

NOUVELLES APPLICATIONS – RTM/Vacuum infusion



©TDL Technique/Egide



©Amplitex/Bcomp



©PowerRibs Bcomp
– Electric GT



©Lincore-Depestele – Multiplast process
Pathé Clichy Paris

New developments

A la une , Bonnes pratiques , Voile

Route du Rhum 2022 : Un bateau en fibre de lin pour Roland Jourdain



Anaée Droubay

30 août 2022 • 3 minutes de lecture



ROLAND JOURDAIN P. #2

We Explore

🇫🇷

📅 Date d'arrivée	🕒 Heure d'arrivée
25/11/2022	21:36
🕒 Temps de course	
16 j, 7 h, 21 m et 0 s	



New developments



6^{ème} colloque fibres
naturelles et polymères
15 Septembre 2022

Smart Circular Bridge
Pont Circulaire Intelligent

Dr Martijn Veltkamp, responsable conception des structures, FiberCore



@fibercore-europe.com

1

New developments

TEMCA
MATERIAUX COMPOSITES



Pour ce projet, les **brise-soleil en composite lin-verre biosourcés** offrent une solution vertueuse qui respecte les **normes énergétiques**

New developments

livMatS Pavilion



[livMatS Pavilion](#) | [Institute for Computational Design and Construction](#) | [University of Stuttgart \(uni-stuttgart.de\)](#)

Current market in France by sector and fibre type

Typologie de matériaux		Type de fibres et renforts		Taux d'incorporation en fibres végétales (%)	Volume produits en France (tonne/an)
Isolants	Isolants souples	Fibre [cm], isolant		> 90	7 200
	Isolants de remplissage	Bottes		100	4 600
Bétons	Enduits, mortiers, blocs/parpaings	Granulat		20 à 50	40 000
Panneaux de particules	Panneaux de particules allégés	Granulat		90 à 95	330 000
Composites	Pièces plastiques injectées	Fibre [mm], Compound		20 à 30	6 000
	Pièces thermocompressées à base de non-tissés	Isolants de remplissage		50	3 000 à 4 000
	Composites à fibres continues	Non-tissé, ruban, unidirectionnel, multiaxial...		30 à 50	± 7 000*

Source : FRD 2019

* capacité de production

Evolution at horizon 2030 in France

Période	Isolants biosourcés	Bétons biosourcés	Composites biosourcés
2006	5 000 t * (0,25 %**)	4 100 t * (0,15 %**)	9 500 t (nrs **)
2012	125 000 t (9 %**)	140 000 t (0,7 %**)	29 000 t (9,7 %**)
2020	200 000 à 250 000 t (13 à 16 %**)	230 000 à 310 000 t (1,1 à 1,5 %**)	100 000 t (23 %**)
2030	200 000 à 500 000 t (11 à 27 %**)	250 000 à 750 000 t (1 à 3,1 %**)	140 000 à 250 000 t (19 à 35 %**)

Evolution prévisionnelle de la consommation de matériaux biosourcés en France - bois inclus
(Sources : ADEME 2007 et 2014)

* Pour 2006 : hors isolant semi-rigide et rigide à base de bois pour les isolants biosourcés, et hors béton de bois pour les bétons biosourcés

** Parts de marché des matériaux biosourcés

➤ **Growing tonnage and market share**

➤ **Significant growth rate of 5 to 20% depending on the applications**

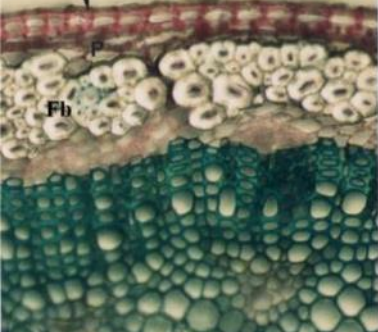
Sémi-produit ou produit fini	Taux de croissance annuel
Isolants souples	+ 10 % / an
Isolants de remplissage	
Enduits, mortiers, blocs/parpaings	
Panneaux de particules allégés	Stable
Pièces plastiques injectées renforcées en fibres végétales	+ 15 à 20 % / an
Pièces thermocompressées à base de non-tissés	Stable
Composites à fibres continues	+ 5 à 10 % par an

Hypothèses médianes de croissance des principaux marchés des matériaux bases fibres végétales techniques hors bois – Source : FRD & IAR

Reading tips

- **FRD (2020) "Mémento 2020 Panorama des marchés fibres végétales techniques matériaux (hors bois) en France",**
<https://www.f-r-d.fr/etudes/m%C3%A9mento-2020/>
- **JEC technical book (Editions 2012, 2014, 2018) "Flax and Hemp fibres: a natural solution for the composite industry",**
<https://www.jecomposites.com/product/flax-hemp-fiber-composites-a-market-reality-the-biobased-solutions-for-the-industry/>
- **Berzin et al. (2017) "Composites polymers et fibres lignocellulosiques : propriétés, transformation et caractérisation",**
<https://www.lavoisier.fr/livre/industries-chimiques/composites-polymeres-a-base-de-fibres-lignocellulosiques/berzin/descriptif-9782746247772>
- **Bourmaud A, Beaugrand J, Shah D. U., Placet V & Baley C (2018) Towards the design of high-performance plant fibre composites. Progress in Materials Science, 97, 347-408.** <https://www.sciencedirect.com/science/article/pii/S0079642518300653>
- **Le Moigne et al. (2018) Surface and interfaces in natural fibre reinforced composites. Springerbriefs in molecular science.**
<https://link.springer.com/book/10.1007%2F978-3-319-71410-3>
- **Müssig, J. (2010). Industrial applications of natural fibres: structure, properties and technical applications. John Wiley & Sons.** <https://onlinelibrary.wiley.com/doi/book/10.1002/9780470660324>

Annexes



Biocomposites properties

Main influencing parameters ?



(Matrix properties)



Fibre orientation

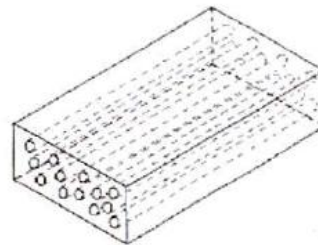
Fibre type and
properties

Mechanical performance
of composites

Porosity

Fibre content

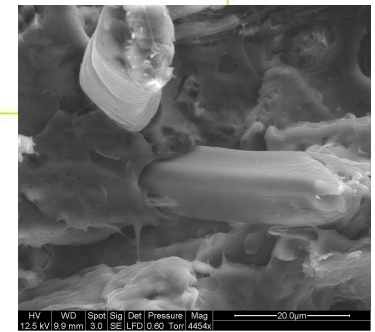
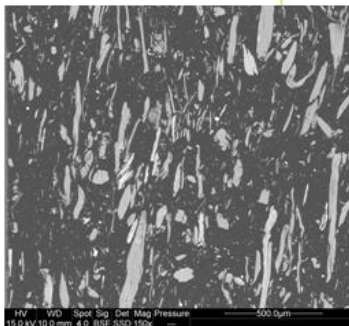
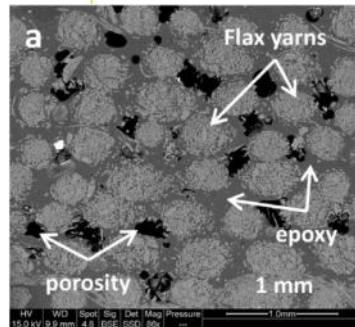
Fibre length



Fibre
impregnation
and packing

Fibre/matrix interface
properties

Relative humidity



Biocomposites properties

A. Effect of fibre properties : epoxy based biocomposites with various fibres

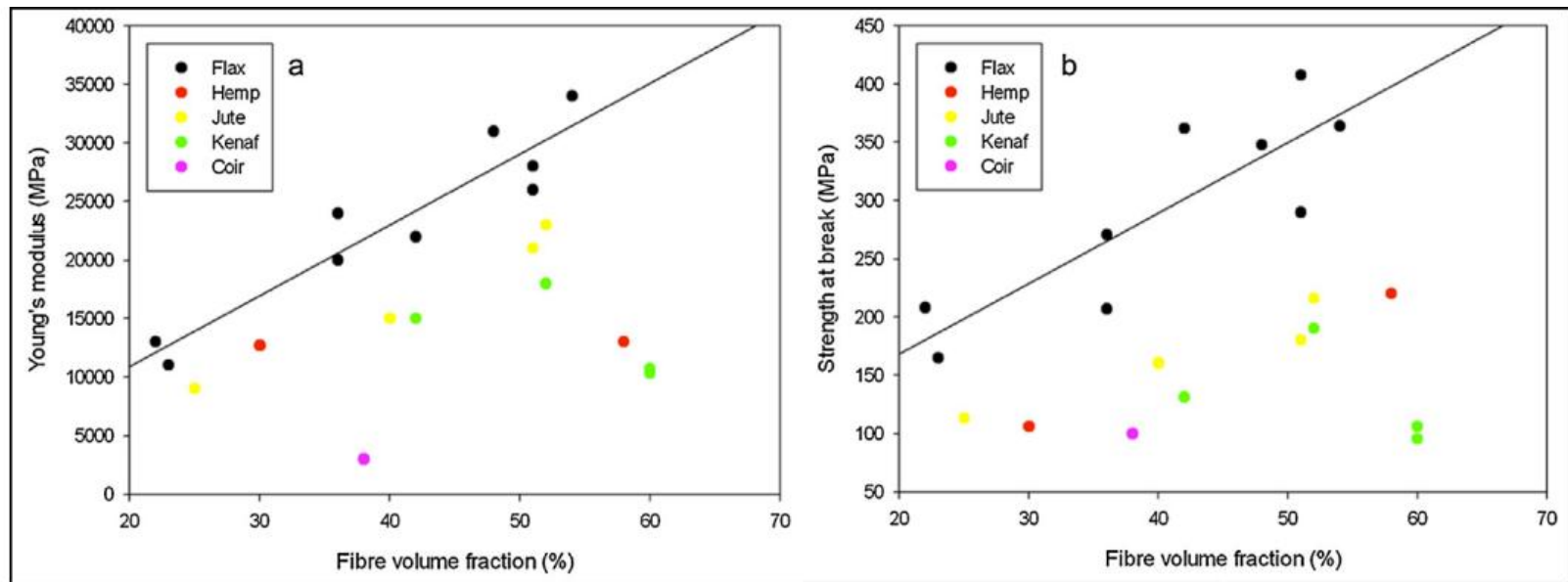


Fig. 37. Young's Modulus (a) and strength at break (b) of unidirectional composites made of epoxy and flax [260], hemp [507], jute [508,509], kenaf [510] and coir [511] fibres.

Biocomposites properties

A. Effect of fibre properties : PP based biocomposites with various fibres

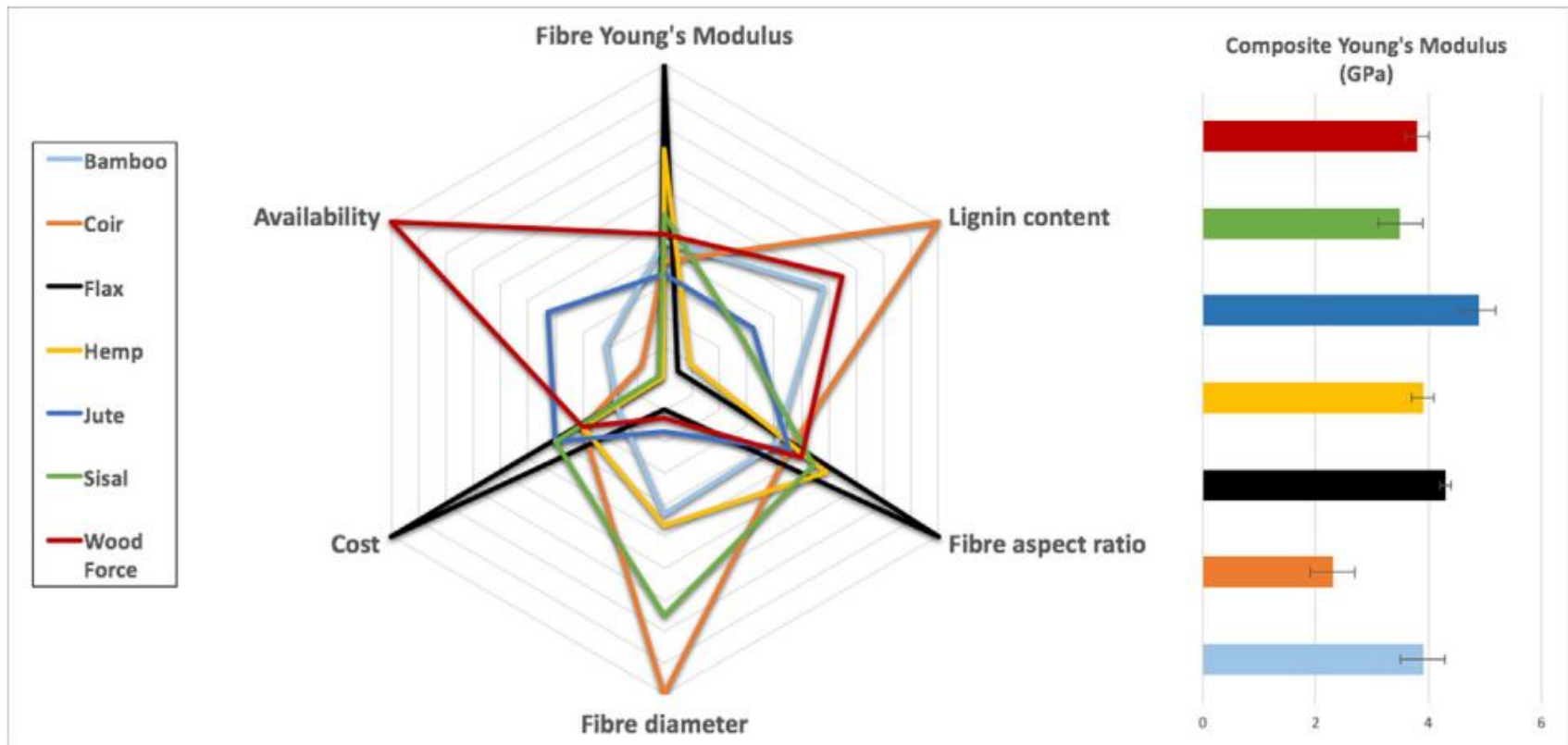


Fig. 38. Main plant fibre properties and associated injected PP composites [99,503,512,513].

Biocomposites properties

Main influencing parameters ?



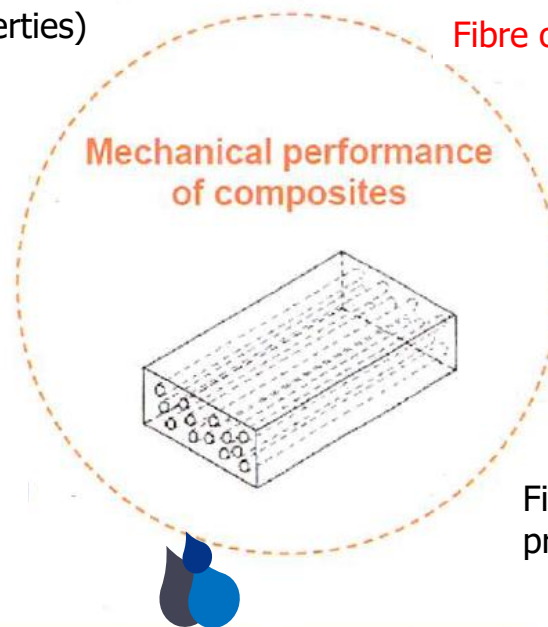
(Matrix properties)



Fibre orientation



Fibre type and properties



Mechanical performance of composites

Porosity

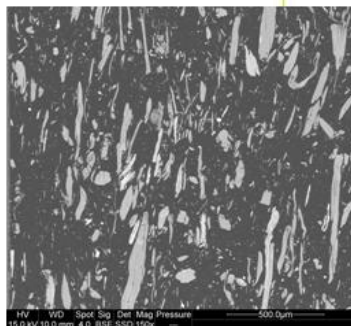
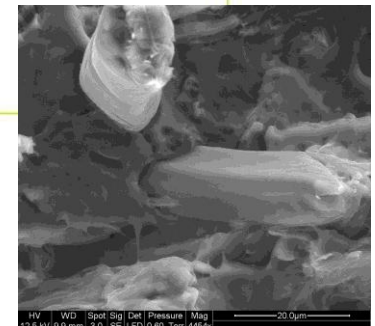
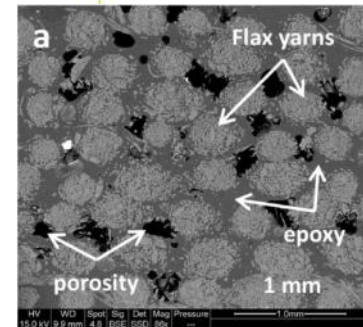
Fibre content

Fibre/matrix interface properties

Relative humidity

Fibre length

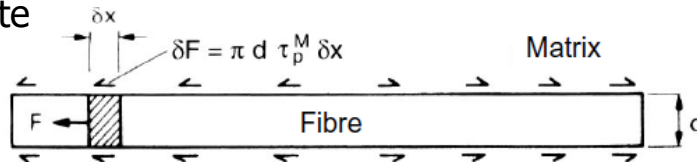
Fibre packing ability



Biocomposites properties

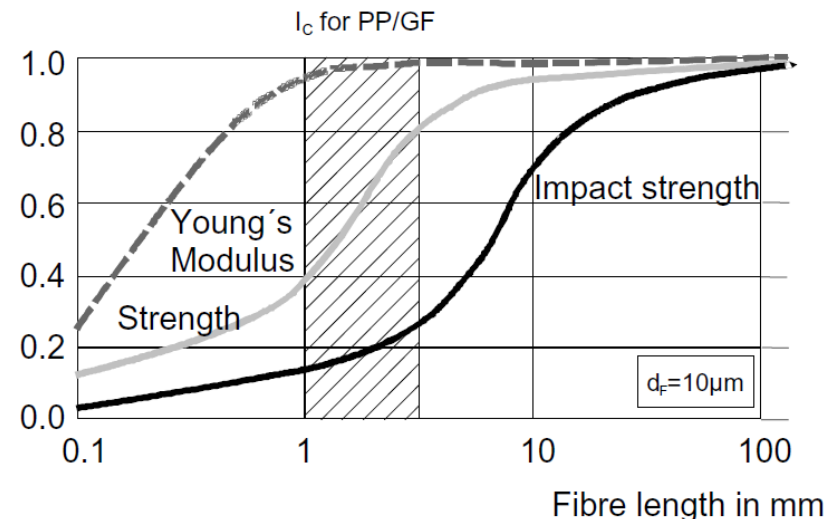
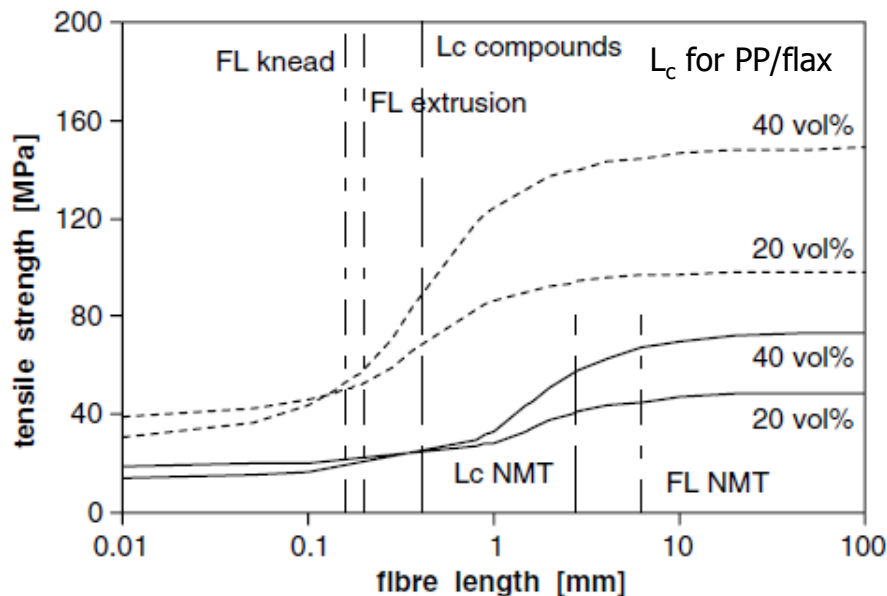
B. Effect of fibre length / aspect ratio on mechanical properties

- **Critical fibre length L_c** = minimum length for the fibres to be loaded up to their failure within the composite



- Kelly-Tyson model that defines L_c :
$$L_c = \frac{\sigma_f d}{2\tau}$$

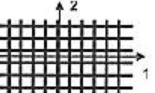
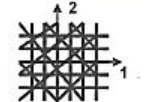
- When $L > L_c$, mechanical properties of short fibre reinforced composites are greatly enhanced and can be similar to long fibres reinforced composites



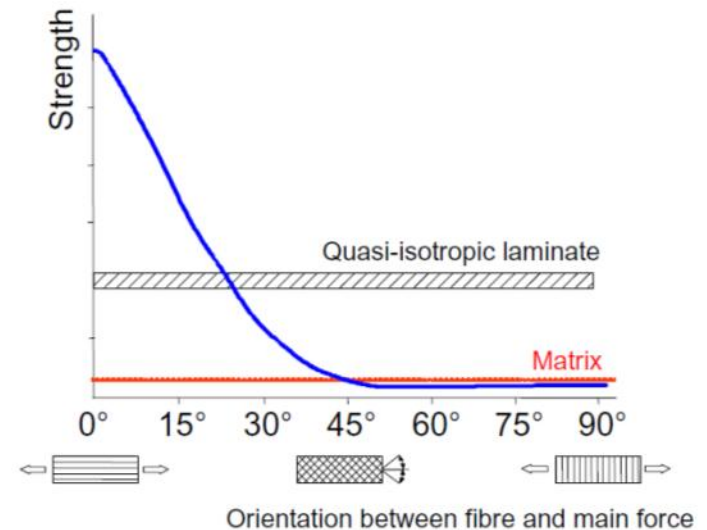
➡ Influence of fibre length on composite material characteristics

Biocomposites properties

E. Effect of fibre orientation : from Unidirectional to 3D fabrics

Reinforcement	Image and coordinate system (for laminates: Axis 3 is normal to the image plane)	flax/epoxy		
		E11, E22 GPa	G12, GPa	ν_{12}
UD		39.5 4.4	2.4	0.311
Cross-ply 0/90		23 23	2.4	0.061
Plain woven, crimp 1.5%		15 15	2.2	0.023
Quasi-isotropic 0/45/-45/90		17 17	6.7	0.283
Tri-axial braid 0/60/-60, crimp braiding yarns 1%		17 15	5.8	0.267
Knitted jersey		6.5 6.0	2.7	0.301

➤ From anisotropic to quasi-isotropic properties



26(Ehrenstein, 1986, S. 80 .- adapted presentation)

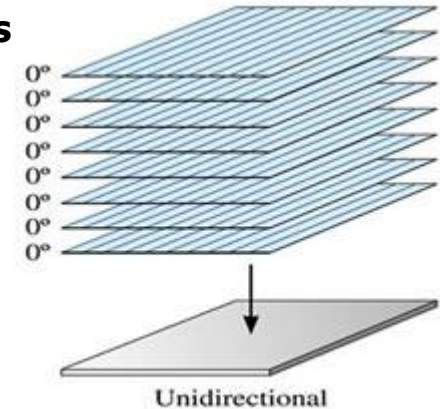
Jörg Müssig / Biocomposites & Natural Fibres / 2008/2009

Biocomposites properties

D. Effect of fibre volume fraction : case of UD composites

- Several **micro-mechanical model** can be used to predict the **stiffness and strength** of biocomposites (short or long fibres)
- Most of them consider a **perfect interphase**
- Case of UD composites :

$$E_c = E_f V_f + E_m V_m$$



$$\sigma_c = \sigma_f V_f + \sigma_m V_m$$

