BOOK OF FINAL RESULTS

SSUCHY

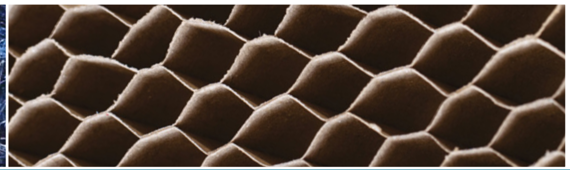
DEVELOPING ADVANCED BIO-BASED **COMPOSITES**

BBI JU

Bio-based Industries Consortium

Horizon 2020
European Union Funding
for Research & Innovation









1 FOREWORD

Vincent Placet

FEMTO-ST Institute, University of Franche-Comté

SSUCHY COORDINATOR

Global warming and climate change are causing dramatic upheavals that already affect every region on Earth. Measures must be taken immediately to rapidly and massively reduce greenhouse gas emissions and strive for carbon neutrality in 2050. The industry and transport sectors are among those which emit the most CO2. In this context, it is necessary to develop new families of **sustainable high-performance materials** that do not derive from petroleum. Plant **biomass** is a prime source to fuel such developments. Indeed, the CO2 sequestered by plants during their development make this resource an excellent carbon sink. However, the major challenge remains to process such biomass into products with advanced functionalities while maintaining carbon neutrality or at least by limiting environmental footprint. It requires to limit energy consumption and CO2 emissions throughout the **life cycle** of the material and the associated products. If the concept has already be proven for some convenience goods and products, it still remains a major challenge for engineering products and structures with complex technical requirements.

To meet such challenges with strong environmental and technical constraints, innovative ideas must be formulated and deployed, bridges and collaborations must be established between academic research and industry as well as between many disciplines, new value chains must be built and developed locally. A **sustainable** European bio-based industry is essential to reach these ambitious goals of continuing the technological development and prosperity of our societies while protecting the environment and ensuring innovation. Within the SSUCHY project, the consortium brought its stone to the building. I hope you will enjoy this Book of Final Results, whether keeping up to date with the results and outcomes, or discovering the wide range of the achieved activities.

Ana Ruiz

Circular Bio-based Europe Joint Undertaking (successor of BBI JU)

SSUCHY PROJECT OFFICER

The project SSUCHY is a success story for BBI JU and has greatly contributed to its goals. After 4 and a half years of work, the project has successfully ended by developing bio-based composites with advanced functionalities for applications in transportation and in high value market niches (acoustic and electronics sectors). In addition, the project's partners have importantly invested in building human and research capacities for the bioeconomy. All in all, SSUCHY has been fully aligned with the European Green Deal objectives contributing towards a greener, circular and bio-based economy.

Circular Bio-based Europe Joint Undertaking   Bio-based Industries Consortium

2 ABOUT SSUCHY

A logic of sustainable development

Recently, the composites sector renewed its interest in plant fibres of various origin alongside polymer **building blocks** derived from lignocellulosic feedstock. Plant fibres are interesting from both technical (e.g. specific mechanical & **damping** properties) and sustainable aspects (e.g. renewable resource, low production cost, creation & preservation of agricultural employments). The other face of the biobased composite lies in the **bio-based** polymers which can be a good opportunity to further use under-exploited wood fractions instead of burning them.

The use of plant fibres is increasing outstandingly and demand is expected to grow by

300 %

over the next 25 years.

From lignocellulosic feedstock (hemp and wood) to bio-based composites with advanced functionalities for transportation and high value market niches

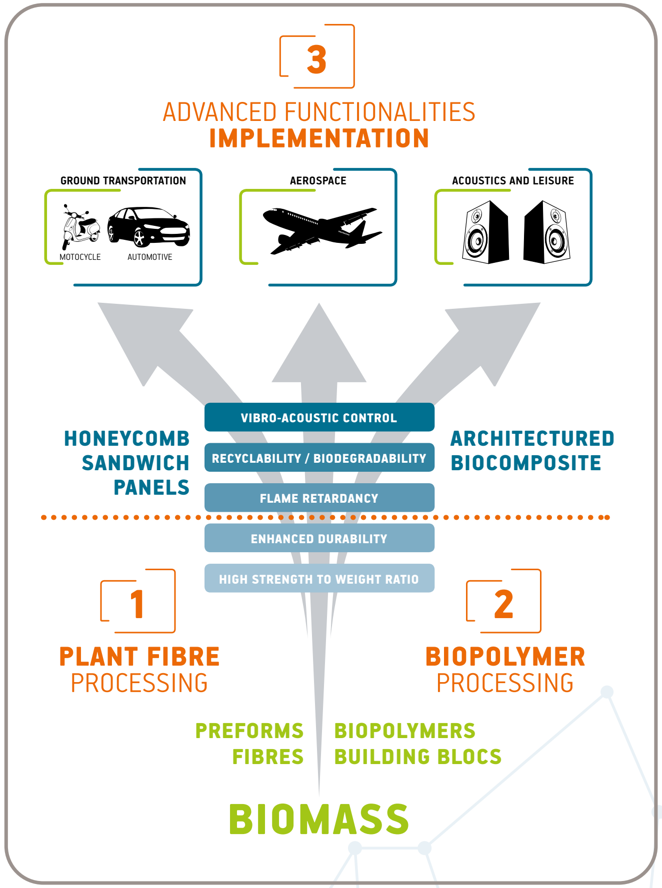
In that context, SSUCHY project contributed to build a bio-based composites value chain from hemp and wood feedstocks with technologies ranging from Technology Readiness Level (TRL) 4 to 5.

The project had, in particular, three main ambitions:

1. Contribute to the development and optimization of competitive hemp fibre reinforcements;
2. Contribute to the development and optimization of bio-polymers with advanced functionalities and tailored for PFCs manufacturing;
3. Implement advanced functionalities in plant-based composite materials and structures and prove the concept at the scale of demonstrators.

To achieve that ambition, the project has used **technologies** and **materials** developed within its frame, alongside market available solutions when the materials developed in the project did not meet the basic quantity or quality requirements for prototyping a product. SSUCHY is impacting the composite sector by improving functionalities such as **loadbearing resistance, weight reduction, enhanced durability, vibration damping, vibro-acoustic control and fire retardancy.** Innovation was demonstrated at the scale of half-products, prototypes and product demonstrators in composite polymers and reinforcements, transportation (ground transportation and aerospace) and a high value market niche (acoustic and electronics).

SSUCHY's approach was implemented within the framework of a multi-level eco-efficiency approach covering experimental aspects, modelling, design, process optimization and complete Life Cycle Analysis of the developed products.



▲*SSUCHY value chain – From Biomass to biobased composites applications*

Main impacts

The expected impact of SSUCHY Project is twofold and notably contribute to three of the Sustainable Development Goals*:

- **New hemp reinforcement for composite application.**
- **New bio-based composite structures and products and demonstration of their advanced functionalities at demonstrator level:**
  1. bio-based floor and trim panels for automotive application,
  2. bio-based monocoque scooter frame,
  3. bio-based panels for electric aircraft interiors application and designs of structure parts,
  4. high-performance green loudspeaker system.
- **Sustainable management and efficient use of natural resources** such as **hemp and wood** and their **by-products.**
- **Decrease CO_2 emission** by substituting petroleum-based materials by **low-weight bio-based composites and products.**
- **Increase the sustainability and the competitiveness of the European bio-based composite sector** through the development of **innovative materials and process technologies.**

Key figures

PROJECT DURATION

54 months

from September 2017 to February 2022

BUDGET:

Total cost:

7,411,150.71 €

BBI JU contribution:

4,457,194.75 €

17 PARTNERS FROM 7 COUNTRIES:

10 academic institutions

3 SMEs

3 industries

1 competitiveness cluster

What are the Sustainable Development Goals?

The Sustainable Development Goals (SDGs) also known as "The Global Goals for Sustainable Development" are a collection of 17 global goals designed to be a blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including poverty, inequality, climate change, environmental degradation, peace and justice. The SDGs, set in 2015 by the United Nations General Assembly and intended to be achieved by the year 2030, are part of a UN Resolution called "The 2030 Agenda".

The Bio-Based Industries Joint Undertaking (BBI JU) Programme

SSUCHY benefited from a contribution of 4.45 million euros from the Bio-Based Industries Joint Undertaking (BBI-JU), a public-private partnership between the European Union (via the EC) and the Bio-Based Industries Consortium (BIC), developing sustainable and competitive bio-based industries in Europe. Its mission is to implement, under the European Horizon 2020 rules, the Strategic Innovation and Research Agenda (SIRA), developed by the industry and validated by the EC.

The objectives of BBI JU are:

- Demonstrate technologies that enable new bio-based chemical building blocks, materials, and consumer products and bring them closer to the market to replace fossil-based alternatives.
- Develop business models that foster the collaboration between stakeholders from across Europe along the entire value chains.
- Set up flagship biorefineries that deploy such technologies and business models to demonstrate that cost and performance of bio-based products are competitive with those of their fossil-based alternatives.

By theses means, the Bio-based Industries Joint Undertaking (BBI JU) wants to contribute to a more resource-efficient and sustainable low-carbon economy, as well as increase economic growth and employment, in particular in rural and coastal areas.

Until today, BBI JU has funded 142 bio-based innovation projects involving 1,055 beneficiaries from 39 EU Member States and Associated Countries.

Horizon 2020
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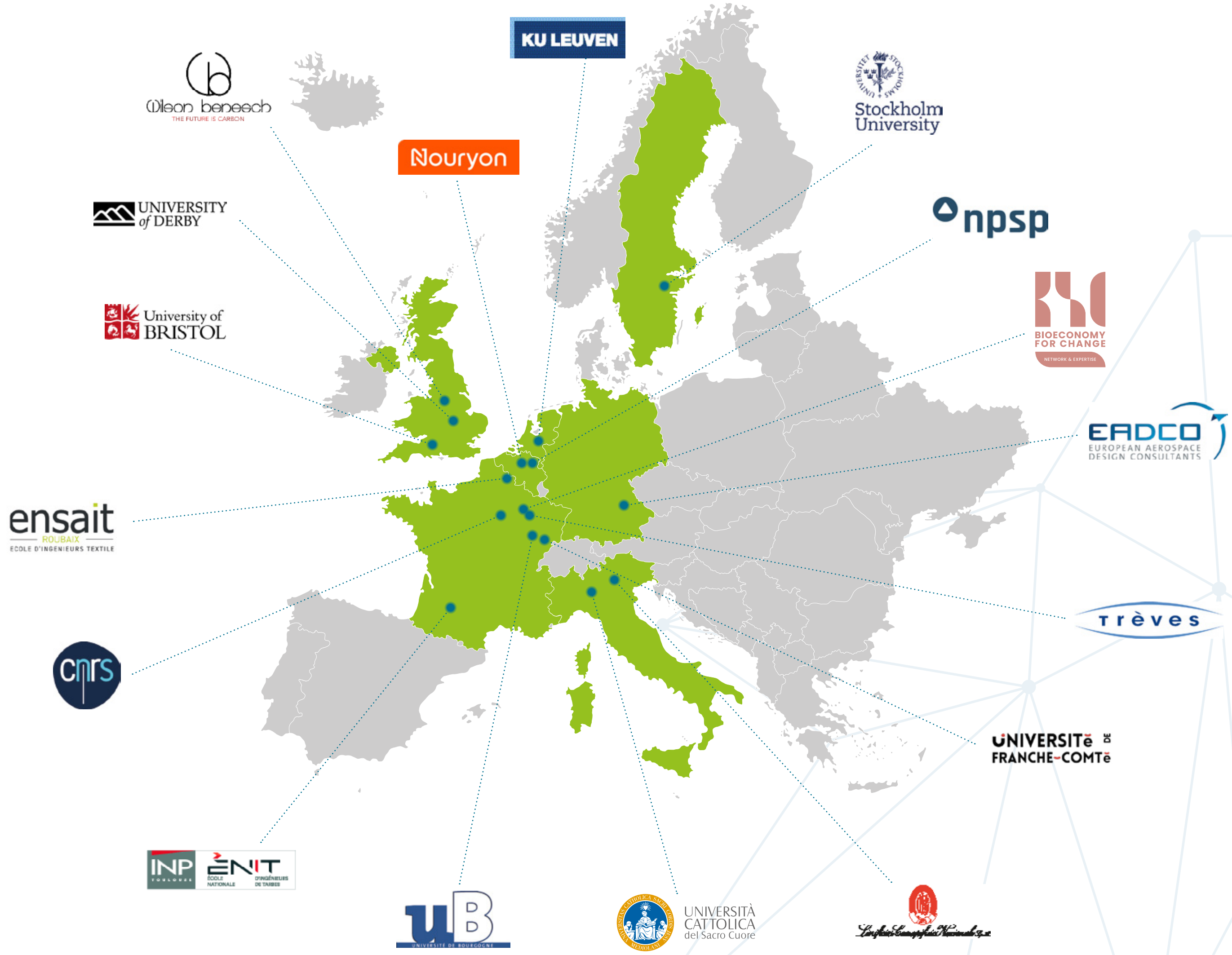
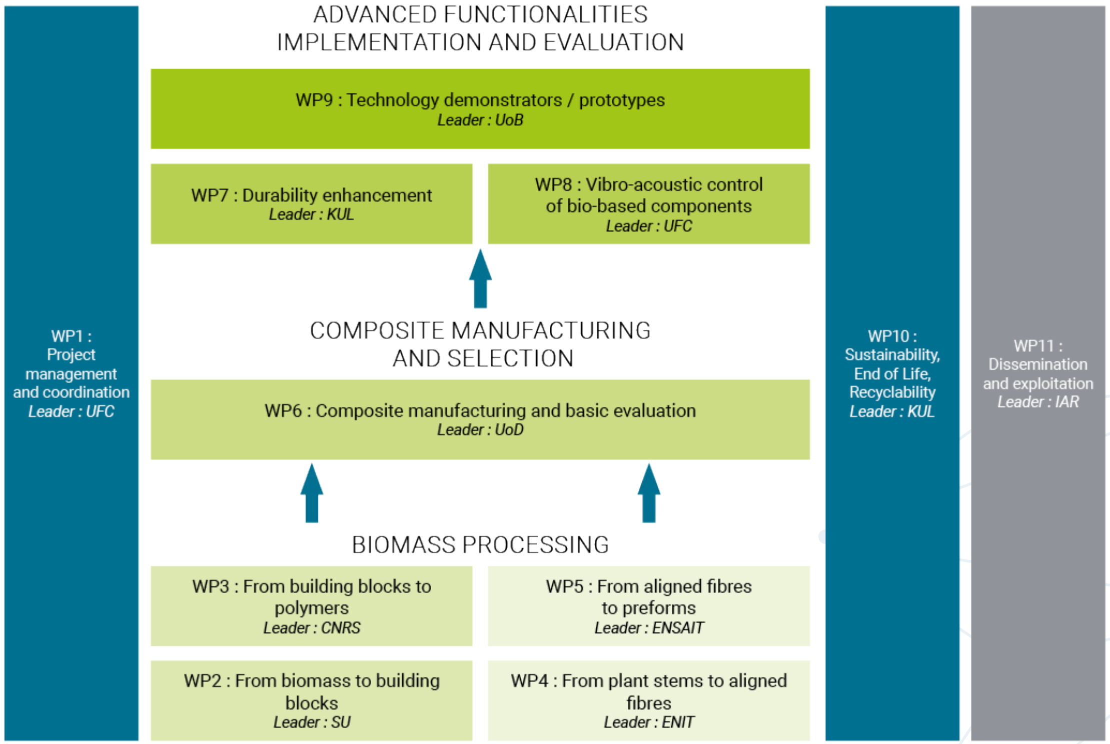
A large-scale multi-stakeholders project



The Consortium counts 17 partners from 7 European Countries, including academia, SMEs and industries, under the coordination of UFC/FEMTO Institute (France). SSUCHY's consortium covers the overall value chain: it starts from the biomass supply, followed by the transformation processes step related to plant fibre reinforcement on one hand and biobased polymers on the other hand, up to the design and manufacturing of actual composites & sandwich material and finally the prototyping of products.

Converting undervalued hemp and wood feedstocks into greener engineering products ▸



◂ *Schematic representation of SSUCHY project structure*

Université de Franche-Comté – FEMTO-ST
FRANCE

Université de Franche-Comté (UFC) is the project coordinator. Different research teams from UFC and its third party ENSMM (Ecole Nationale Supérieure de Mécanique et des Microtechniques), belonging to the FEMTO-ST institute, contributed to all the Work Packages (WP), with a main focus on mechanical characterization and modelling of biopolymers, plant fibres and plant fibre composites. FEMTO-ST led the Work Packages 6 and 8 focused on the mechanical characterisation and on the vibroacoustic behaviour of plant fibre composites, respectively, and Work Package 1 dedicated to the project management.

Bioeconomy For Change (ex-IAR)
FRANCE

Bioeconomy For Change (previously called IAR), as an innovation cluster on bioeconomy, defined, implemented and monitored the communication and dissemination strategiese within Work Package 11, aiming at maximizing the impact of SSUCHY's outcomes among its various stakeholders. They strongly worked with the Coordinator and all SSUCHY's partners to share the results obtained on several types of network.

KU Leuven
BELGIUM

Within SSUCHY, KU Leuven was leading Work Package 7 – Durability enhancement dedicated to characterization and improvement of the durability of plant fibre composites. KU Leuven was also leading WP10 on the study of Sustainability, End of Life and Life Cycle Analysis. The teams involved also participated in WP6 for testing the impregnated fibre bundles of hemp yarns as well as further developing furan bio-composites.

Stockholms Universitet
SWEDEN

Within SSUCHY, the SU team was involved in WP2 that aimed at converting biomass into buildings blocks. Its main tasks were to generate monomeric compounds from lignocellulosic feedstocks. This both involved a technique developed by the SU team to perform a fractionation process on the woody biomass by applying a tandem organosolvant pulping together with a catalytic depolymerisation reaction as well as further functionalizing the generated lignin derived monomers into suitable building blocks for the composite manufacturing. Thereby, an iterative process between the SU team with the KUL and UFC/UoB teams for durability and vibro-acoustic control has been pivotal for success of this project, where the functionalization of the monomers was tailored for different applications.

Centre National de la Recherche Scientifique – ENSCP
FRANCE

CNRS and its Research Institute of Chimie Paris (IRCP) led the WP3 on the transformation by chemical processes of bio-based building blocks into functional polymerizable synthons suitable for biocomposite applications and the development of bio-based thermoplastic approach which encompasses organic, organometallic and polymer chemistry as well as homogeneous catalysis. Their work was developed in strong collaboration with the group of Green Chemistry and Sustainable Polymers (GG-CSP) of Université de Bourgogne.

University of Bristol
UNITED KINGDOM

The University of Bristol was leading WP9 that aimed at applying the materials and simulation procedures developed in the previous work packages into design and prototypes at TRL4. The team worked on material characterisation (thermophysical, mechanical), composites manufacturing, modelling and design of foams/cores for vibroacoustics and structural integrity.

École Nationale d'Ingénieurs de Tarbes
FRANCE

Within the frame of the SSUCHY project, ENIT was leading the WP4 which objectives were to obtain from specially selected hemp varieties a range of yarns with different levels of properties (mechanical, deformability, and surface) and price suited to multiple end uses of composite materials. Its main task consisted in producing and modelling the behaviour of innovative textile products at the scale of the yarn from hemp plant stems (WP4). Within the WP5, ENIT collaborated with ENSAIT to perform deformability and friction tests of textiles at the scale of woven, knitted or braided fabrics. The last contribution of ENIT was about the multiple recycling of thermoplastic composites by using two different mechanical processes in collaboration with KUL.

Nouryon
NETHERLANDS

Nouryon, previously AKZO Nobel, is leader in essential chemistry for a sustainable future and was mainly involved in WP7 on Durability and its main task was to develop a novel cobalt-free curing system for bio-based resins. The solution had to meet certification specifications and needed to resist to the presence of water presence.

Linificio e Canapificio Nazionale Srl – Marzotto Spa
ITALY

As an industry company, the main task of LCN in SSUCHY project was the production of hemp material suitable for composite. Its was to provide to the transformation of hemp from stems to preforms, including the yarn making and weaving processes.

Trèves
FRANCE

The main goal for Trèves, a recognized automotive supplier specialist in acoustic and thermal comfort that also brings new functionalities to the market was to substitute oil-based sandwich "semi-structural" technologies like the Baypreg (GF/PU) used for trunk loadfloors or package tray applications for example by lightweight 100% bio-based composite sandwich with both almost continuous natural fibres reinforcements as well as bio-matrices binders either thermoset or thermoplastic with excellent static punching, creeping, humidity and vibration damping properties.

Wilson Benesch
UNITED KINGDOM

As a SME company with specialty in very high-quality acoustic devices, Wilson Benesch provided manufacturing and assembly capability for production of test samples and prototyping of functional components for integration into subsystems for testing. They applied existing expertise in composites construction technology gained within the working practice of the company.

EADCO GmbH
GERMANY

EADCO has an experience in international aircraft development; within SSUCHY they defined and realised possible applications of environmentally friendly in aircraft interiors (mostly sandwich panel structure) based on natural fibres and alternative matrices. EADCO also contributed to cross-industry recommendations for the adoption of bio-based materials given the strict certification requirements, mainly related to fire performance, weight, and mechanical properties.

NPSP BV

NETHERLANDS

As a SME company with specialty in design and manufacturing of various bio-based composite materials, NPSP focused specifically on one of the demonstrators for ground transportation application: improving a monocoque scooter frame. They notably worked towards tackling the problems of vibration absorption.

École Nationale Supérieure Arts & Industries Textiles

FRANCE

ENSAIT and its GEMTEX laboratory was the leader of WP5 dedicated to the manufacturing of natural fibres preforms used as reinforcement for composite materials. Its work consisted in defining the preform architecture and characterizing the mechanical properties of dry preforms. This work was closely linked to WP4 (raw material and aligned fibre/yarn scale) alongside WP6 (composite manufacturing) in collaboration with ENIT, UFC and KUL partners.

Université de Bourgogne

FRANCE

The University of Bourgogne was involved through Green Chemistry and Sustainable Polymers group (ICMUB). They mainly worked on WP3 dedicated to the transformation of building block into polymers and specifically focus on the development of functional biobased epoxy thermosets. They are in very close collaboration with Chimie ParisTech–CPT partner.

Università Cattolica del Sacro Cuore – CERZOO

ITALY

UCSC was mainly involved in the WP4 dedicated to obtain selected hemp varieties and specially to improve the hemp culture conditions by modulating a set of agronomic parameters (i.e. plant density, nitrogen level and time of dew retting). They greatly rely on previous work involving selection of the best combination of agricultural techniques to obtain hemp stems leading to high-fibre yields combined to high performance mechanical properties. They also worked on primary processing steps carried out in the fields - i.e retting – and used a previously developed model to help with designing optimal hemp cultivation and retting in various environments.

University of Derby

UNITED KINGDOM

The Institute for Innovation in Sustainable Engineering (IISE) is the University of Derby's latest investment to support advanced manufacturing and engineering companies. IISE work collaboratively with industry to research and develop sustainable solutions within engineering. The main tasks in SSUCHY included computational design, design for manufacturing, experimental characterization, prototyping, manufacturing of moulds/tools using in-house machining capabilities mainly in WP6.

The benefit of the advice of two external experts

The External Expert Advisory Board brought together two experts of bio-based polymers and composites. They both provided an external and independent view on the project, critically reviewed and gave feedback to the project progress in order to ensure its relevance and excellence and advised the consortium on the scientific topics and orientation.

It was a privilege to act as external expert for the SSUCHY project. From the very beginning, I was impressed by the quality, the diversity, and the complementarity of the research consortium, covering all aspects of hemp fibre and its composites. The start was not easy, just because of the many different topics which had to be addressed. But great progress has been made, not only in almost all of the work packages, but even more in the mutual understanding, interaction and intensive collaboration between the different teams spread over Europe.

Em. Prof.Dr.-Ing. Ignaas Verpoest, *KU Leuven*

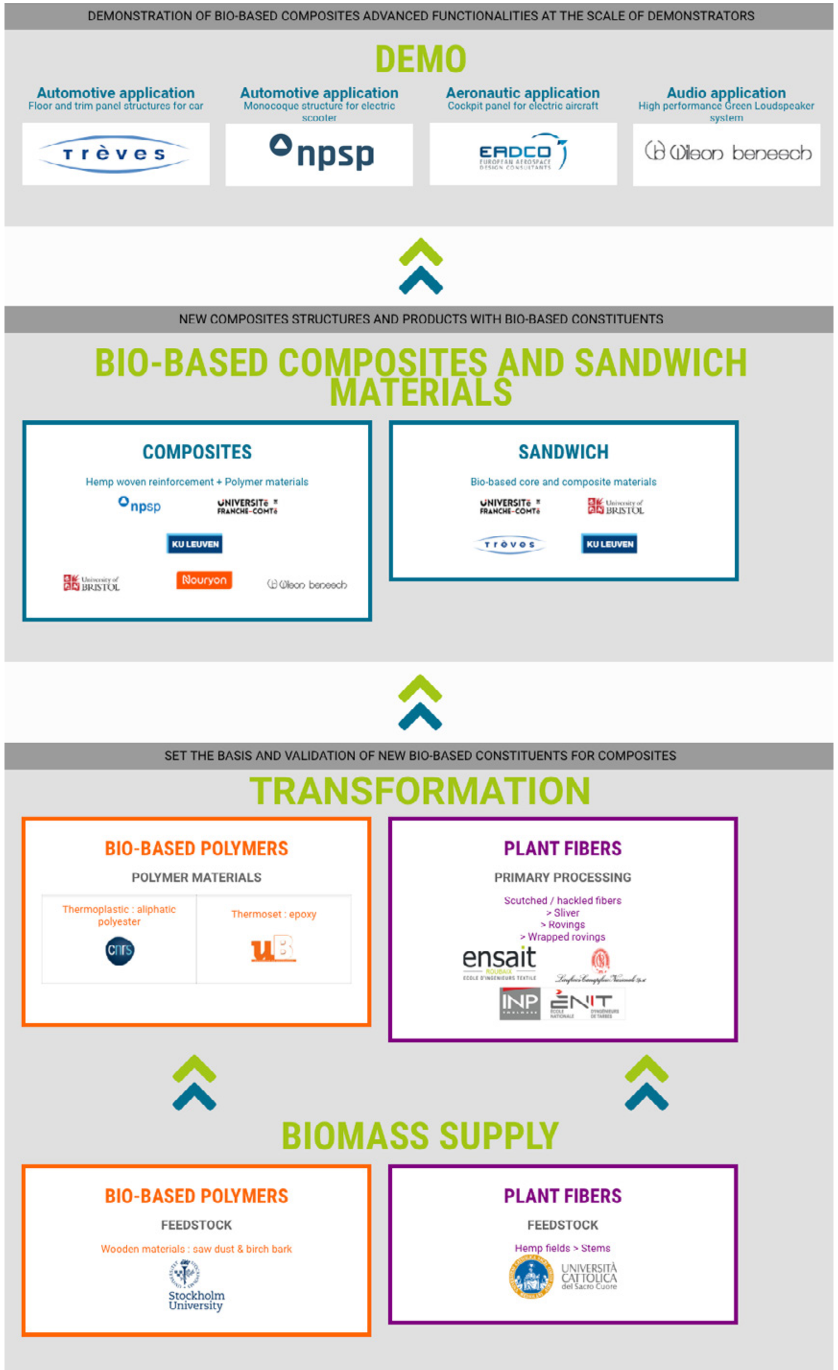
It was a great pleasure for me to join my respected colleague Ignass Verpoest as an external reviewer for the SSUCHY project. A broad thematic scope drove the SSUCHY project from cultivation to the finished product along the entire process chain. This transdisciplinary project has led to fascinating results, excellent publications, and new product ideas. I am sure that the project results will help fibres from the European hemp plant to find new applications in innovative composite materials to a greater extent in the future.

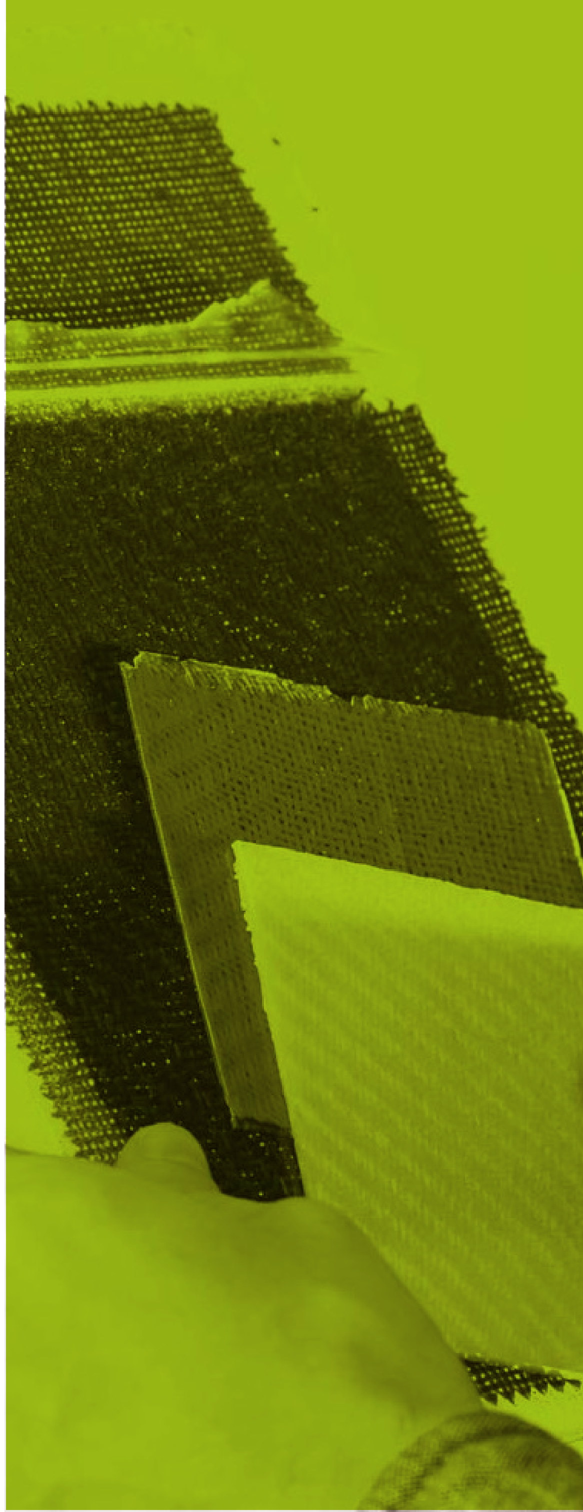
Prof. Dr.-Ing. Jörg Müssig, HSB - *City University of Applied Sciences, Bremen, Germany*

3 RESEARCH

In order to achieve the expected objectives set at the beginning of SSUCHY project, the work carried out was divided into several work packages, all closely related to each other and allowing to cover a complete value chain illustrated in Figure 3. This "research" section details the main achievements obtained before being incorporated and demonstrated at industrial scale, in the following section.

SSUCHY concept covering a complete value chain ▸





3.1. Biomass supply and transformation: to set the basis and validation of new bio-based constituents for composites

3.1.1. BIO-BASED POLYMERS - FROM FEEDSTOCK TO POLYMER MATERIALS

The objective of the work conducted within the first two work packages of the project is to fractionate biomass by tandem organosolv/catalysis approach to generate value added lignin-derived monomers, from currently considered **waste** streams, and to tailor design them to synthetise thermoset and **thermoplastic** polymers in a sustainable manner.

The use of green chemistry to process feedstock into monomers by means of LCA

Current biorefineries, such as pulp mills, were developed a century ago and are focused on the cellulose stream and consider the rest of the biomass as energy source. Since the last decades there has been an increasing interest to utilize these other streams for higher value applications. In the SSUCHY project we have considered using lignin from both different wood sources as well as bark.

These 4 different sources of lignocellulosic **raw material** that were evaluated as feedstock to produce monophenolic compounds for **thermosets** were:

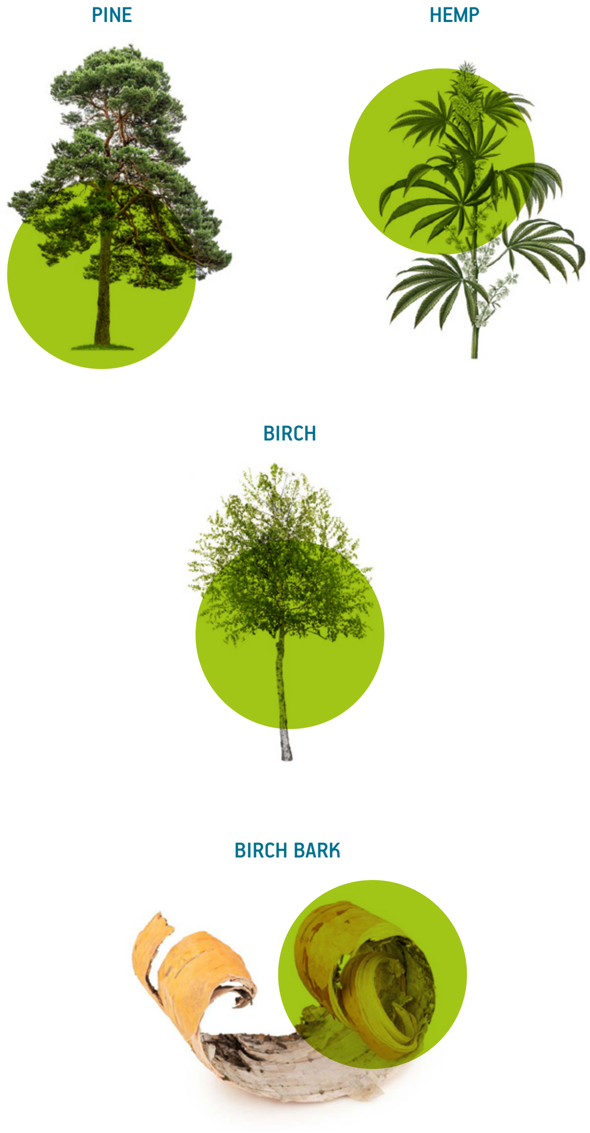


Figure 1: Four different sources of raw material were used to produce monophenolic compounds

The first step is a **catalytic fractionation** of the raw material to produce different fractions and then to separate the monophenolic compounds from the lignin rich fraction. The second step is to convert these monophenolic compounds to substrates comprising a diepoxy functionality. In a first iteration, these substrates have then been cured for thermosets and evaluated for physical and mechanical properties. In this first iteration, it was found that guaiacyl derived substrates, from spruce and pine, worked well whereas syringyl ones from birch or hemp did not (10.1021/acssuschemeng.1c06607[1]). Thus, the focus was directed towards the guaiacyl derivatives from spruce and pine that were firstly found in pine which is a softwood and later in birch bark.

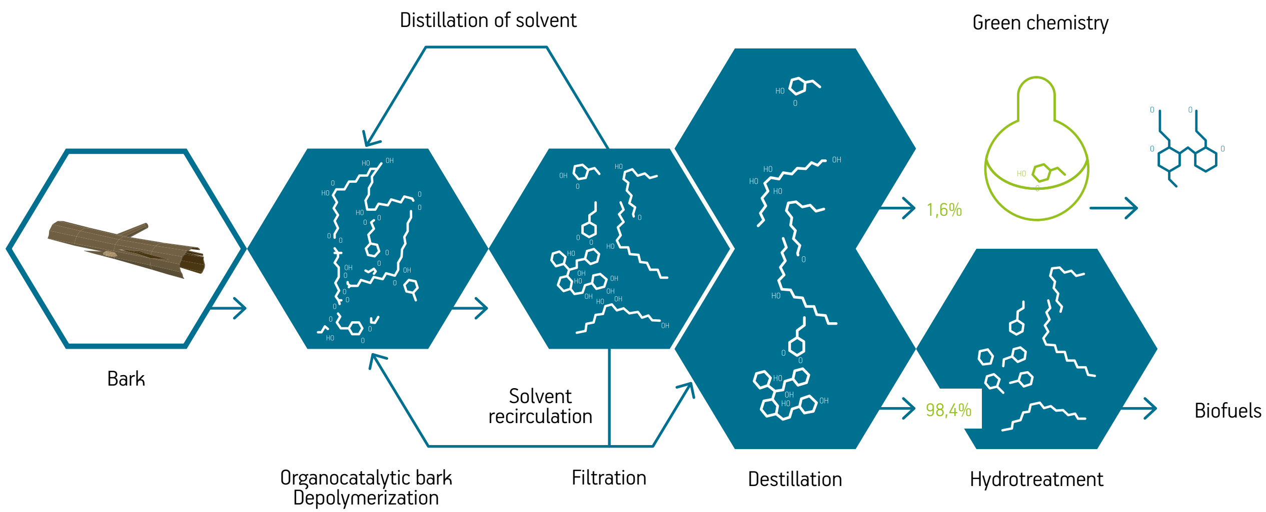
Both the team at Dijon and Stockholm worked hard to develop a green and sustainable route to the diepoxy-isoeugenol doi.org/10.1016/j.crci.2017.10.005[2]; 10.3390/polym12010229[3]; 10.1021/acssuschemeng.9b02629[4]). However, there are challenges with this substrate both when it comes to the chemical synthesis of the diepoxy substrate but also the fractionation to yield the monomer. Even if 100% of the chemical bonds in lignin that the methodology is selected towards cleaving are broken, a maximum of 10% of the starting wood is converted to the monophenolic compounds. We were able to increase the theoretical maximum yield, however this developed methodology was more efficient with hardwoods than softwoods (doi.org/10.1038/s41557-021-00783-2[5]). The rest of the wood has a low quality and thus this route was found less sustainable.

After iterations with the team working on sustainability, end-of-life and recyclability and discussions within the consortium, a new source of raw material that could give both a guaiacyl derivative as well as other fractions of high quality was searched for. It was found that in birch bark, which is a hardwood, a compound called ferulic acid is present. We were able to first develop a catalytic fractionation of the birch bark, and then convert the depolymerized material to biofuels using hydroprocessing. In an iterative collaboration with sustainability team, we were able to develop a procedure from birch bark to biofuel with a positive LCA (doi.org/10.1039/D0GC00405G[6]). In this first publication, no efforts to extract out the ferulic acid derivative were made.

However, an intense investigation was initiated where we were able to use birch bark and first perform the catalytic fractionation to yield depolymerized material which comprised small amounts of ethylguaiacol that has a potential to be a building block for green polymers. Even though only 1.6% of the ethylguaiacol could be distilled off, the rest can go to biofuel, so no wastes are generated and this is important for a positive LCA. A novel diepoxy substrate was then developed by first dimerizing the ethyl guaiacol with **renewable** formaldehyde, and then reacting this intermediate with epichlorohydrin to form the diepoxy bisguaiacol. After good evaluation of the mechanical properties of the compound upon curing and also compatibility with the hemp fibre, it was decided develop a green and sustainable route to generate this compound, and we were able to do this after several iterations. An efficient solvent recovery system was key to reduce the environmental impact of the overall transformation.

Thus, a low-valued raw-material, birch bark, has been valorized to biofuels and a monomer for green and sustainable thermosets, giving an overall positive LCA.

Figure 2: The optimized value chain coproduces biofuel and starting material for a green and sustainable transformation to diepoxy bisguaiacol.

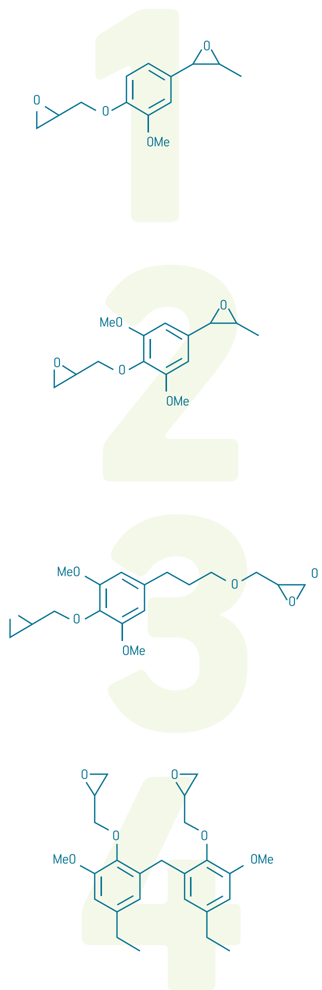


Towards the design of bio-based polymers and composites

The main objective of the Paris and Dijon teams involved in this task was to use the bio-based synthons prepared by the Swedish colleagues (or commercially available derivatives), as polymerizable functional building blocks for the design of organic matrices dedicated to bio-based **composite** applications. The challenges were therefore: i) to develop new alternatives to commercial petroleum-based or partially biobased resins, in order to significantly increase the proportion of renewable raw material in their compositions (or even to target a fully bio-based composition), ii) to maintain thermo-mechanical properties compatible with structural applications and defined by the project specifications (in particular a **glass transition temperature**-T_g above 100°C). Thus, two distinct **polymerization** pathways, involving the development of innovative thermosetting and thermoplastic matrices, respectively, were considered in the SSUCHY project.

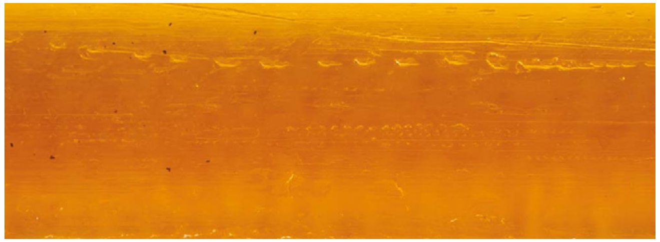
The thermoset approach:

Glycidyl ether of Bisphenol A **(DGEBA)** is largely the main precursor for the production of epoxy resins (roughly 90% of world-wide market), exhibiting high thermo-mechanical performance well suited to structural composite applications. However, the possible harmful effects on health and the exclusively petrochemical origin of DEGBA make it necessary to consider replacement molecules, more sustainable and derived from biomass. In this regard, several diepoxidized **prepolymers,** prepared in Stockholm and derived from aromatic molecules extracted from lignin (Fig. 3), have been implicated in curing protocols in the presence of cyclic acid anhydrides used as **hardeners.** For some formulations, also bio-based acid anhydrides were used, which significantly increased the bio-based carbon content in the matrix (close to 100%).

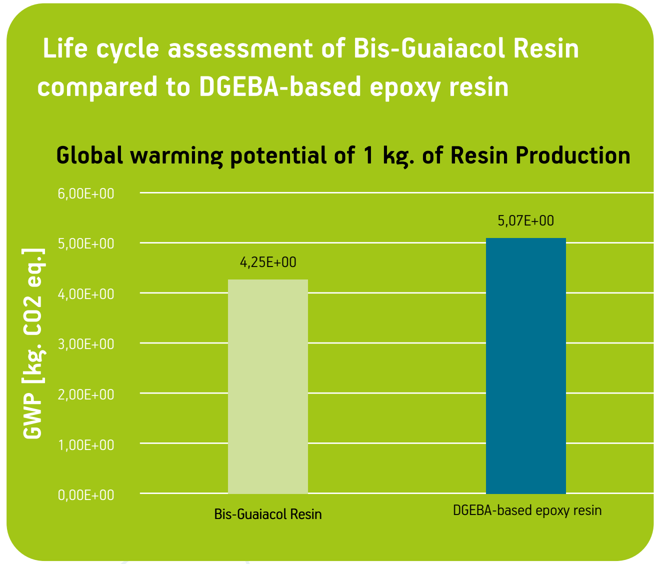


▲ *Figure 3: Diepoxidized building blocks designed from molecules derived from lignin.*

The most promising formulations were obtained with the derivatives of isoeugenol (I) and ethylguaiacol (II) associated with camphoric and phthalic anhydride, respectively. In both cases, glass transition temperature values above 100 °C were measured as well as young modulus values greater than 3 GPa, thus successfully fitting with the specifications established for the SSUCHY's composite applications. With the isoeugenol derivative, an optimized and greener formulation called *BioIgenox* has been developed leading to a significant reduction in volumes of organic solvents employed as well as in the synthesis time [DOI: 10.3390/polym12010229[7]].

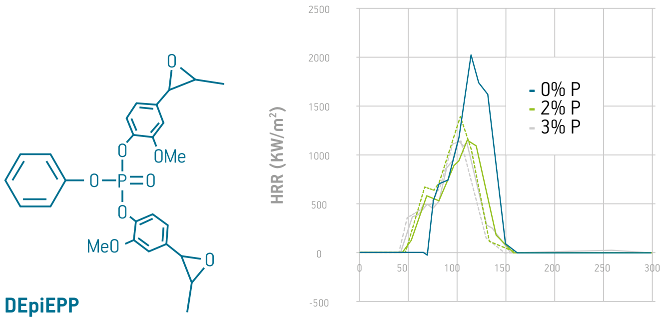


▲ *Figure 4: Sample of fully bio-based epoxy thermoset (BioIgenox)*



The evaluation of bio-based resins was then carried out up to the manufacture of mini-samples using a **thermo-compression** process and incorporating hemp fibres produced by another partner of the consortium. The composites prepared contained a mass fraction of fibres in the range of 35 to 40%. In terms of mechanical properties, the three-point bending tests showed values comparable, or even superior, to those obtained from a matrix based on DGEBA demonstrating the possibility of finding alternative molecules derived from lignin.

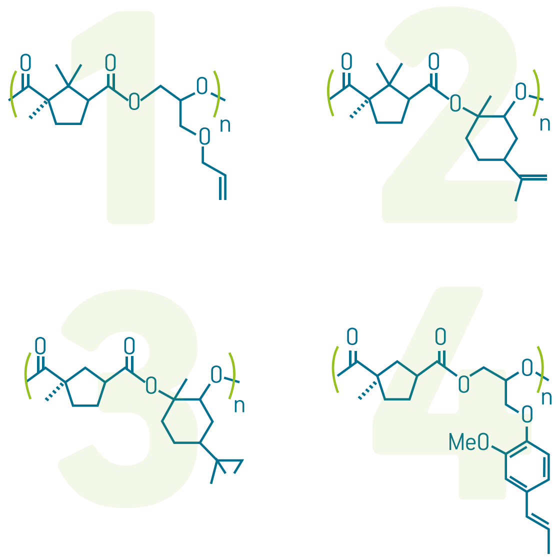
As some targeted applications relate to the field of transport, another part of the project also aimed to improve the fire resistance of the materials designed. Therefore, the synthesis of a new bio-based flame retardant (DEpiEPP) was also developed during the project. Derived from isoeugenol, this compound can be used as a copolymer in combination with other diepoxidized precursors (according to a reactive approach). During cone calorimetry tests, its incorporation into the matrix (up to 3%) increased the rate of residues and notably improved the flame retardancy of resin samples (Fig. 5) [DOI: 10.1021/acssuschemeng.9b02629[1]].



▲ *Figure 5: Molecular representation of the flame retardant developed and its impact recorded by cone calorimetric analysis.*

The thermoplastic approach:

For thermoplastic preparation, our strategy was first to evaluate the feasibility of the synthesis of new polyesters by a one-pot approach, which avoids the formation of side-products, the purification of intermediates and therefore limits the use of large amounts of solvent. Therefore, we were able to develop a green process to obtain camphoric anhydride and to prepare 4 new thermoplastic polyesters (Figure 6). The post-functionalization of the different types of thermoplastics showed an effect on the thermal properties. The results obtained were then close to the specifications targeted in the SSUCHY project. Thus, the 2 most promising thermoplastics (2,3) have been prepared to form mini samples of composite dedicated to bending tests. However, the first experiments performed by our partner at UFC showed that our polymers were too brittle.



▲ *Figure 6: 4 new thermoplastic polyesters*

To avoid this problem, we then decided to use bio-sourced plasticizers such as those used for PLA. From polymers **2** and **3**, UFC partner prepared two samples that were blended with 10% bio-sourced lactide (Figure 6). As the main bottleneck for the 2 most promising polymers was the amount of material obtained, we have been trying during the last months of this project to improve the scale-up but unfortunately, we obtained a larger scale polymer that had a Tg value that was too low.

In order to obtain a more processable material, we then decided to investigate a similar one-pot sequence starting from methacrylic or acrylic acids. Again, this one-pot approach makes it possible to directly obtain biobased materials without needing to isolate and purify intermediates. To form our monomers, we also employed different bio-based alcohols, such as ethyl lactate or vanillin, which is one of the only industrially available aromatic products of lignin. The alcohols used for the polymer preparation give plastics their main thermal or mechanical properties, such as flexibility or hardness. Thus, we have developed a new set of unique **macromolecular** structures from (meth) acrylate esters. For instance, the homopolymer of ethyl lactate methacrylate displayed a *Tg* at 47°C, while the homopolymer of vanillin methacrylate had a glass transition at 111°C, due to its more rigid side chain. The random copolymers we obtained had a single *Tg* while the block copolymers had at least two *Tg*s. In all cases, it was possible to keep a high *Tg* by using vanillin as comonomer (DOI:10.1002/anie.202106640[8]).

3.1.2. INNOVATIVE HEMP VALUE CHAIN FOR COMPOSITE REINFORCEMENTS

The objective of this work was to produce hemp-based reinforcements for composite applications by proposing and optimizing suitable primary (from stems to rovings) and secondary (fabric manufacturing) processing routes. In Europe, hemp is currently processed using mechanical systems such as hammer mills, also known as decorticators, which provide fibres in the form of short and medium-length fibres from disordered straws. This processing method is quite damaging for the fibres and the mean values of their resulting tensile properties are generally lower than for flax. In the SSUCHY project, we investigated two routes. The first one uses the flax value chains for long line fibres and tows from aligned straws and the second one consists in decorticating randomly aligned straws out of the traditional textile flax production zone. In both cases, the goal is to produce continuous aligned reinforcements fabrics from selected hemp varieties, namely Futura 75 and Fibror 79, cultivated and processed in Italy and France, using optimized agronomic, retting (DOI: 10.1016/j.indcrop.2021.113337[9]) and processing conditions.

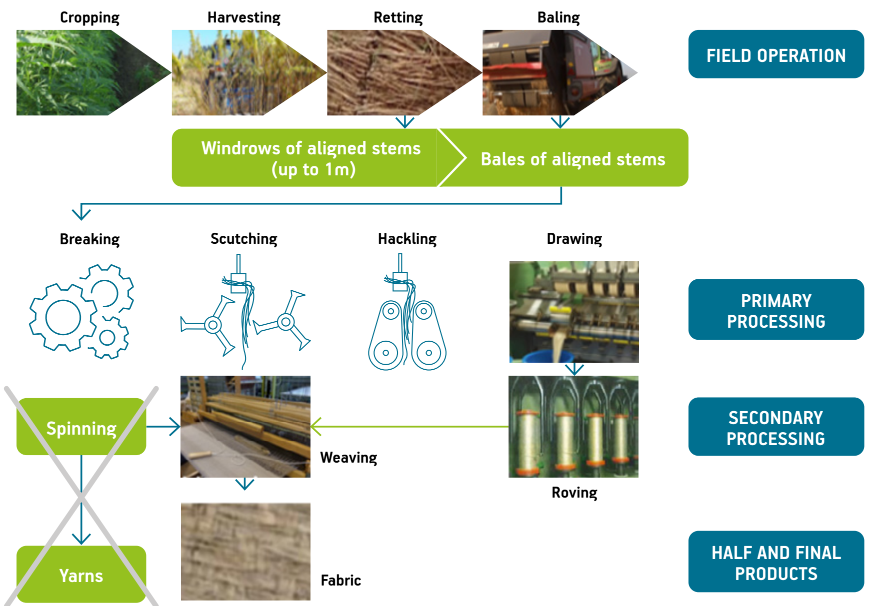


Figure 7: Flax production chain adapted to hemp

Field management and first processing: from the field to the roving (first transformation)

Route 1, as described in Figure 7 into details, follows the traditional method to obtain long fibre flax including the use of the flax machinery. It requires the use of aligned straws and the **scutching/hackling** machines dedicated to flax. The scutching and hackling process parameters were successfully adjusted for hemp stems to obtain high performance fibres combined with high long fibre yields (DOI:10.1016/j.indcrop.2021.114045[10], 10.1016/j.compositesa.2022.106915[35]) Rovings were successfully obtained for reinforcement fabric manufacturing. The secondary processing was also simplified when compared to traditional textile applications since the spinning step was eliminated to reduce the carbon footprint and save time and money while keeping optimised reinforcement potential at composite's scale.

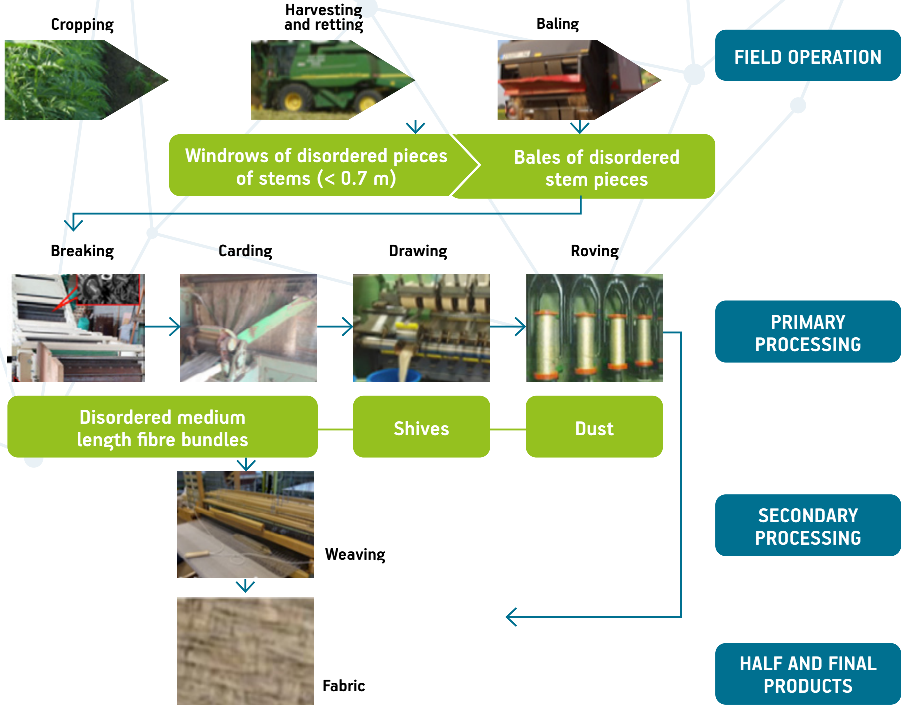
Route 1: Adapted flax fibre route for aligned and parallel straws

As shown by Figure 7, dew retted 1 m long and aligned/parallelised hemp stems were produced by UCSC in 2018 despite adverse conditions (800kg) and in 2019 (3tons). The level of biomass obtained combined to the fibre yield contained in the stems led to possible amounts of fibres of up to 3.8 tons/ha with FIBROR 79 variety. In 2020, hemp stems were purchased to a French cluster to test the possibility of industrial production from hemp cultivated industrially in Europe.

Scutching was performed at the laboratory and industrial scales and after labscale optimisation, specific parameters were transferred to the industrial scale to maximise the long fibre scutching yield up to 18%, about half of the total fibre mass of the stem. The rest of fibres can be valorised as tows using the second route described below. 100% long line fibre based roving type yarns were then manufactured at the industrial scale by Linificio Canapificio Nazionale. About 300 kg of roving type yarns were available for the manufacturing of the specific reinforcement fabrics required by the demonstrators.

Route 2, presented into details in Figure 8, uses a more economical chain (particularly in the field) to extract hemp fibres in which the most important processing tools are breaking rollers and breaking card (DOI:10.1016/j.indcrop.2019.111988[11]). It has the main advantage also not to require aligned stems. The hemp can therefore be processed using traditional equipment for processing hay for example after seed **harvesting** by a combine machine as utilized usually in France and Europe.

Figure 8: Value chain for disordered stems



Route 2: All fibre route suitable for randomly aligned straws

In territories where parallel aligned stems are not available, another fibre extraction route consisting in breaking rollers and breaking card was explored. It is described in Figure 8. This route is expected to be more economical as the field management is performed with classical straw management that most of the farmer possess. The extracted fibres were then transformed into roving type yarns following a direct preparation or after a supplementary tow combing step. About 50 kg of these fibres were transformed into roving type yarns ready for weaving.

The level of reinforcement of the fibres for both routes was shown to be modestly affected by the different fibre extraction and preparation steps. The levels of fibre reinforcement are equivalent for both routes 1 and 2 and are also very comparable to the one of hackled flax [ref Bensadoun et al. doi:10.1177/0731684417695461[12]] used in commercialised reinforcement fabrics (Figure 9). It can therefore be concluded that the hemp fibres as processed in the frame of the SSUCHY project using both routes 1 and 2 are fully suitable for composite reinforcement and can be used for similar parts as the ones targeted by flax.

From both production routes, the objective of the work was to obtain from European grown hemp a range of roving type yarns specially designed for load bearing composite reinforcement purposes and suitable for weaving and **braiding** processing. Low level of twist rovings were manufactured to keep the great potential of hemp fibres as high as possible but nonetheless with a sufficient **tenacity** and low hairiness so that it is compatible with secondary transformation.

From the yarn to the reinforcement materials: Second transformation

After this first body of work to obtain the aligned fibres and roving-type yarns, the next steps were related to the secondary processing, in particular weaving and braiding. This work also contributed to the establishment of requirements and to the optimisation of the textile preforms associated to each demonstrator/prototype as well to the identification of the best textile technology to set up the preforms. More than 15 hemp semi-products resulting from the primary processing were then analysed in view of this secondary processing to evaluate the influence of chemical treatments applied on fibres, the origin of hemp fibres, the **twist level** and the **linear density** of roving-type yarns. The tenacity at break of yarns required for the weaving process is about 15 cN/Tex, which is challenging to achieve with low twisting (Figure 10). An **environmentally-friendly** chemical treatment was successfully applied on the low-twisted rovings to reach this tenacity target without damaging the fibre and their effective properties in composites [DOI: 10.1080/15440478.2020.1761925[13]]. In the rovings produced from the route 2, fibres had more hairiness than those from route 1 fibres, which led to difficulties during weaving. Another strategy consisting in co-warping the low-twisted hemp rovings with very fine thermoplastic monofilaments (PA12 and PA11) was also implemented (Figure 11). The tenacity of this commingled yarn has been improved compared to low-twisted hemp roving and was sufficient to produce woven fabrics at lab scale. [DOI:10.1016/j.matpr.2020.02.307[14], 10.3390/coatings11070770[15]]

Figure 9: Hemp fibre reinforcement potential for both routes 1 and 2 and comparison with hackled flax ▼

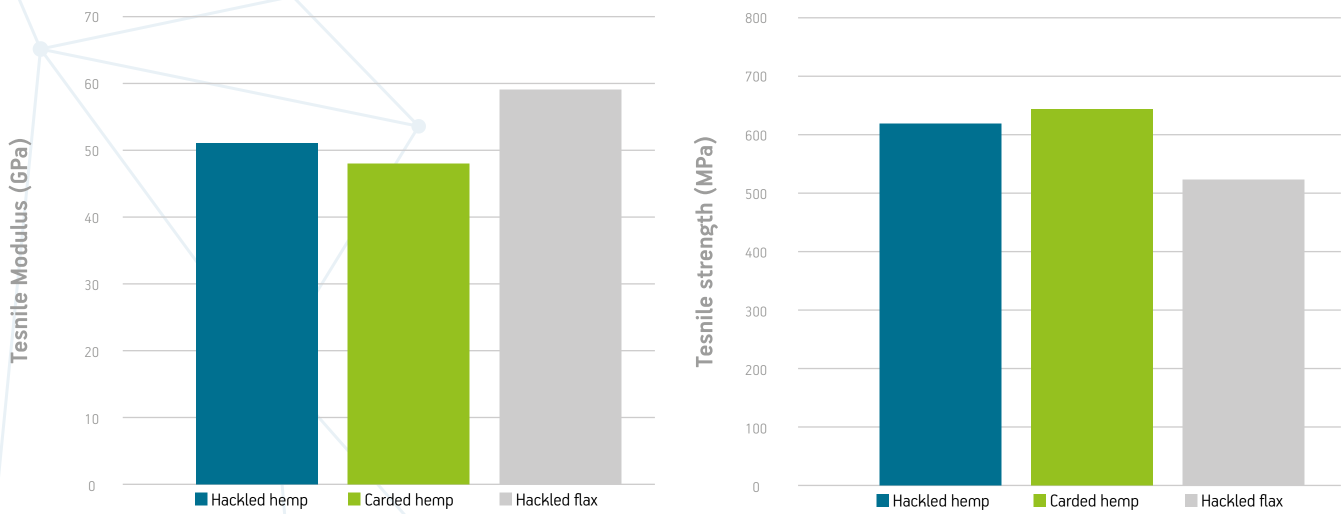


Figure 10: Production of hemp rovings

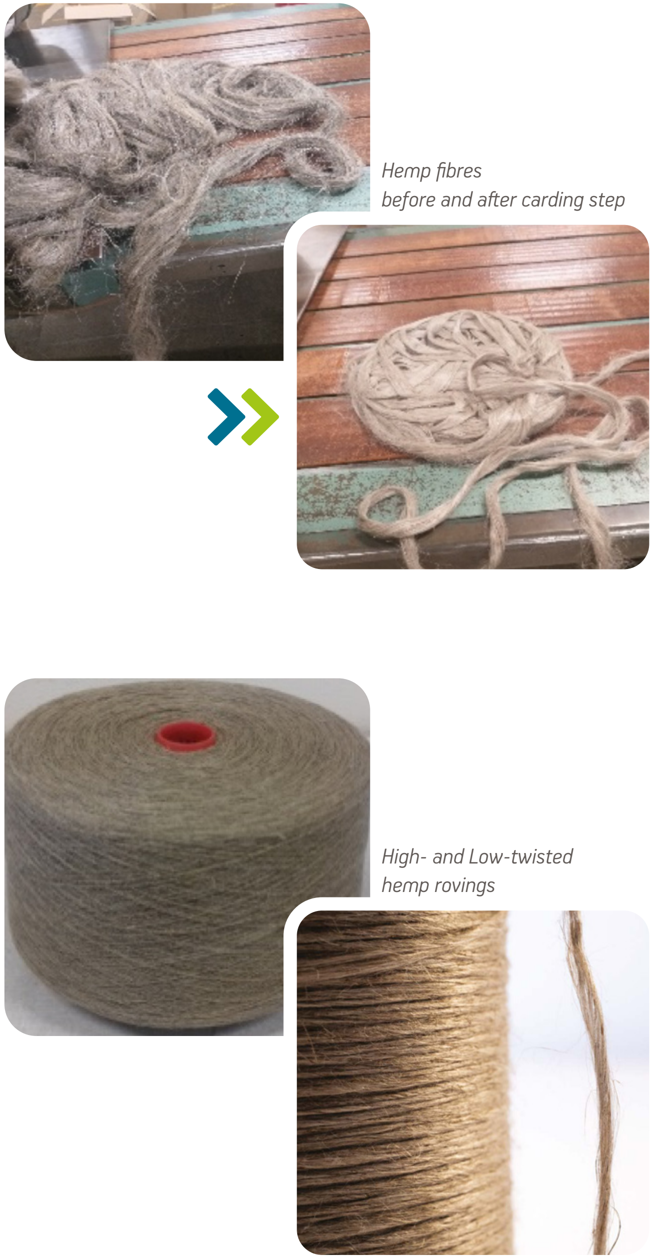


Figure 11: Development of innovative products from HEMP roving commingled with thermoplastic filaments

A variety of 100% hemp reinforcements suitable for composite applications was then produced including:

- balanced and unbalanced fabrics with various weaving diagrams such as satin, twill, plain weave,
- and also quasi **unidirectional** fabrics and braided preforms.

With the low-twisted rovings, more than 20 patterns of hemp woven fabrics have been manufactured at the lab and industrial scales with different weave diagrams (plain weave, twill, satin…). The most optimized fabrics in terms of mechanical properties were produced at industrial scale (more than 250 m^2). A hybrid fabric, produced at industrial scale, was also constituted from rovings from route 2 in weft and rovings from route 1 in **warp.**

The braidability of hemp rovings was also tested and braids were successfully produced (Figure 12). Each architecture imparts different properties to the fabric and the resulting composites. [DOI:10.1016/j.compositesb.2019.107582[17]].

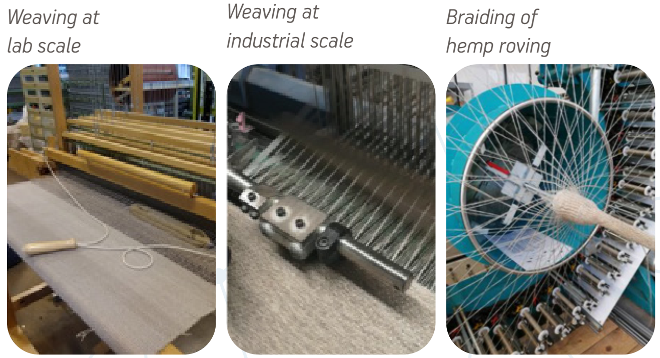


Figure 12: Second transformation from hemp roving to reinforcements for composite

Quasi-unidirectional fabrics were also produced from low-twisted hemp rovings in weft direction, associated with a few fibres in warp direction (3% of fibre content). It led to a fabric with high fibre content (97 % of fibre content) in one direction and low **crimp.** The preforming abilities of these quasi-UD were evaluated and the tensile properties at composite scale were compared to those given in literature from flax fibres.(figure 13) [DOI:10.1177/0021998320954230[18]]

Hemp weaving process

Preforming of hemp quasi-UD

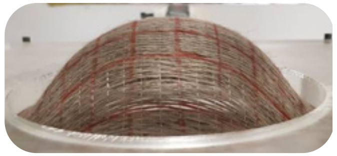
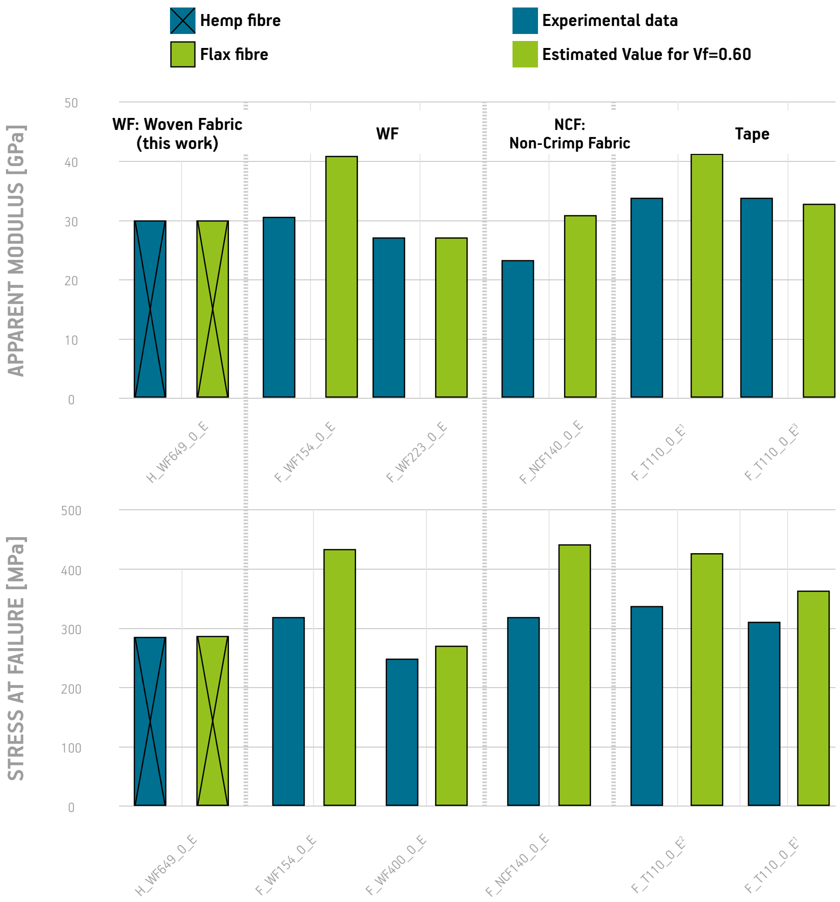
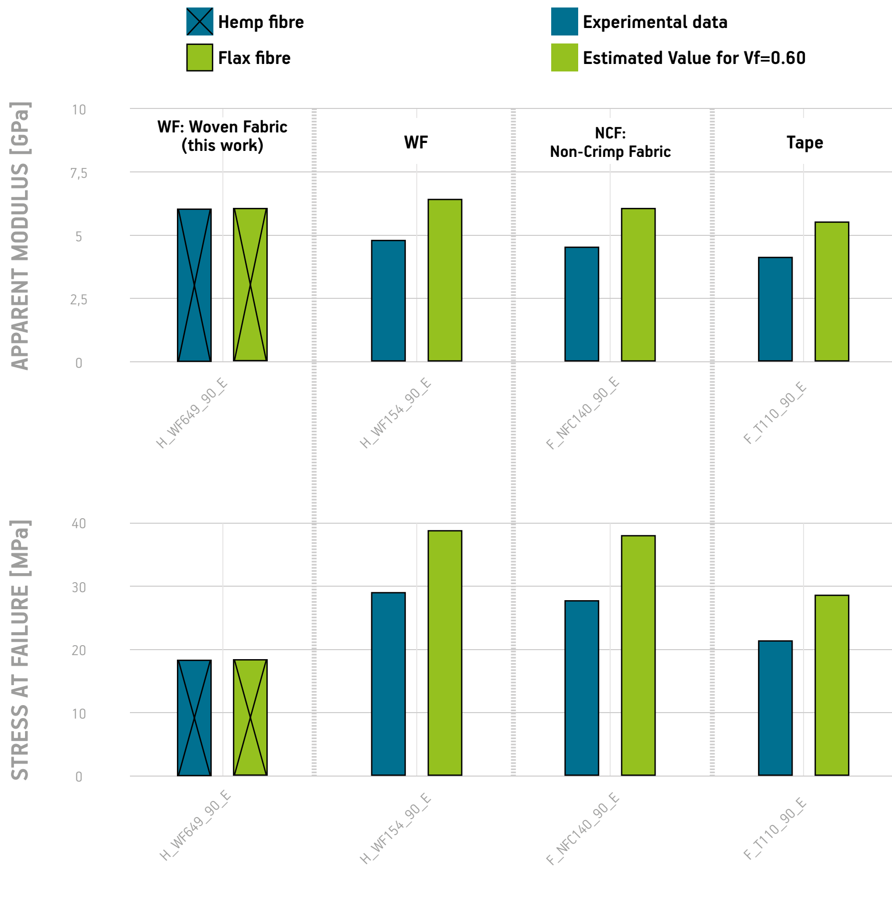


Figure 13: Tensile properties of quasi-unidirectional hemp fabrics reinforced epoxy composites and comparison to flax-based composites [DOI:10.1177/002199832095423018]

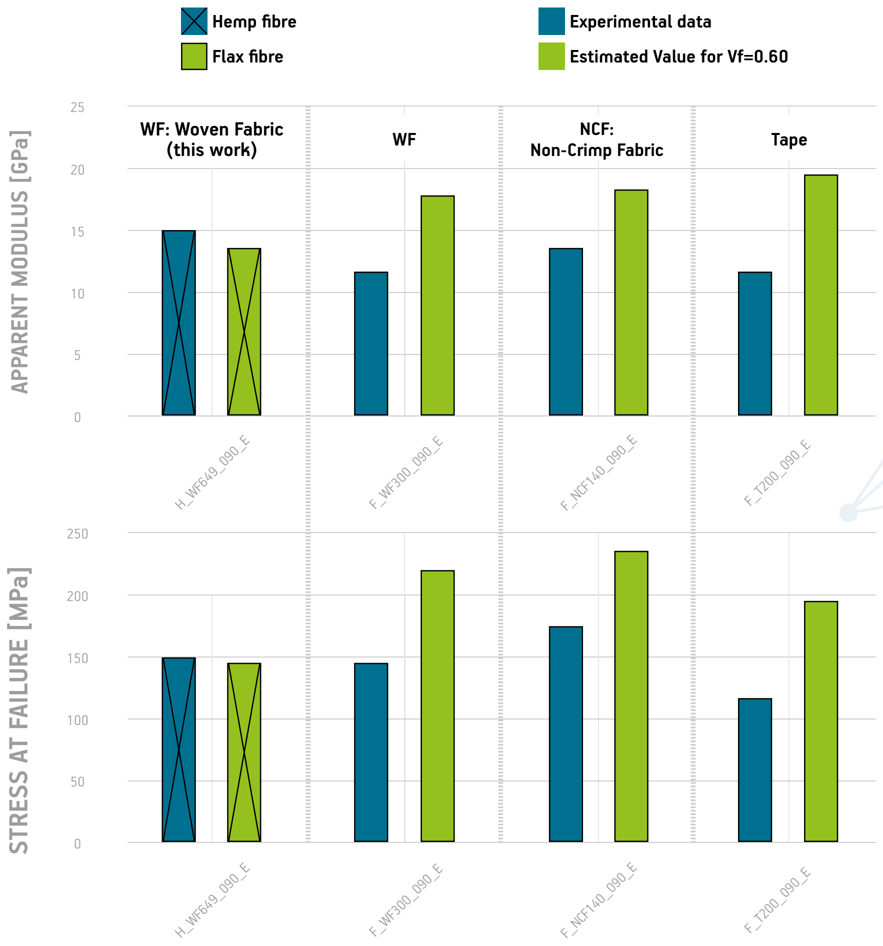
Longitudinal direction of UD composites



Transverse direction of UD composites



Cross-ply composites



Hybrid fabrics mixing hemp and bio-based polymeric filaments such as PA11 were also produced form the commingled yarns. These materials have the main advantage of containing both the reinforcements and the matrix. They offer reduced processing time, consistent with automotive production constraints, the potential for fast, clean and automated manufacturing, as well as infinite shelf life compared to thermoset **prepregs** and recycling possibilities (Figure 14).

Figure 14: Hybrid fabrics from comingled yarns and composite sample

For both routes, low-twisted rovings suitable for weaving were obtained and woven fabrics were then produced. Results demonstrate that using the two paths, hemp can achieve properties comparable to high quality long flax fibres for high performance composites. These primary and secondary processing steps were demonstrated at the lab scale but also using industrial machinery. Innovative products as commingled yarns or quasi-unidirectional fabrics, which did not exist before for hemp fibres, have been incorporated into the SSUCHY library of materials.

Life-Cycle Assessment on Hemp reinforcement

According to the evaluation proceeded on hemp and flax reinforcements, they show 27.3 and 18.4 percent lower Global Warming Potential than the glass fibre respectively.

3.2. New bio-based composites structures and products used and developed within SSUCHY, an overview

A wide range of bio-based composite and sandwich materials were studied during the SSUCHY project to evaluate their processability and performance level. They were manufactured using three categories of constituents: (i) the bio-based polymers and hemp-based reinforcements developed in the project and described in the previous sections, (ii) marketed bio-based polymers such the GreenPoxy 56 by Sicomin, PFA (Polyfurfuyl alcohol) by TFC (Transfurans Chemicals), and PA11 (Polyamide) by Arkema and (iii) marketed flax-based reinforcements, flaxtape and flaxpreg T-UD FR by Lineo-Ecotechnilin, for benchmark purposes, proof-of-concept and demonstrational. These latter were meant also to be used in the early stages of the project, waiting for the development of the SSUCHY constituents.

3.2.1. FULLY BIO-BASED HEMP-EPOXY COMPOSITES MADE OF THE SSUCHY CONSTITUENTS

Fully bio-based composites were produced from the woven hemp fabrics and the bio-based epoxy thermosets (BioIgenox and Bisguaïacol-based epoxy). The obtained composites reach the target in terms of thermomechanical properties, with a Tg higher than 100°C, bending properties comparable and even sometimes surpassing those of DGEBA-based epoxy composites and with a toxicity and environmental impact lower than for the traditional glass fibre reinforced DGEBA-based epoxy composites. This is one of the main achievements of the SSUCHY project and it did establish an interconnection between the wood-derived building blocks and hemp value chains. As a result, a new, innovative and economically-viable value chain is proposed for the development of structural and fully bio-based composites from plant biomass (see Section 5).

3.2.2. HEMP FIBRE REINFORCED GREENPOXY MATRIX COMPOSITES

Woven hemp fabric composites

Woven hemp fibre reinforced composites were also produced with the partially bio-based epoxy resin commercialized by Sicomin (GreenPoxy 56). Results showed that mechanical properties comparable to those obtained with the front-runner flax reinforcements (Flaxtape by Lineo-Ecotechnilin and Amplitex by BComp) can be achieved (DOI:10.1177/0021998320954230[20] ; 10.1016/j.compositesb.2019.107582[21] ; 10.1016/j.compositesa.2020.106204[22].

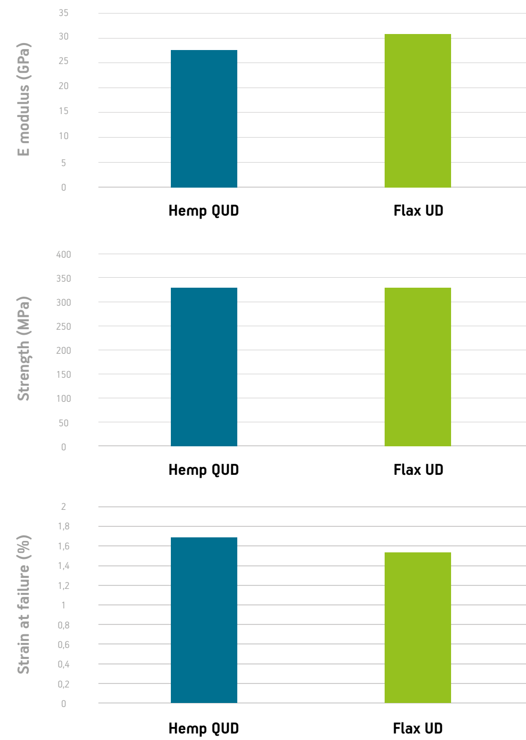
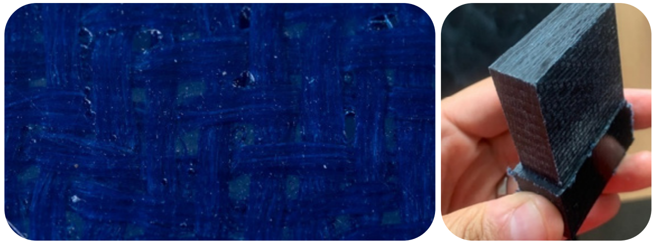


Figure 15: Comparison of the mechanical performance of hemp and flax epoxy composites and fibres (Hemp QUD: quasi-unidirectional woven hemp fabric composite developed within SSUCHY, Flax UD: flaxtape reinforcement by Lineo-Ecotechnilin).

Colored woven hemp fabric composites

Coloured hemp composites were also developed from these constituents (Patent EP3879028A1·2021-09-15[23]). The idea relates to a coloured plant fibre unimpregnated fabric embedded in a transparent matrix for the production of composite materials and products with a specific aesthetic and/or decorative effect. The colour and the aesthetic effect are not obtained, as usually done, by coating the composite product or colouring the polymeric matrix, which generally result in a planar colour. The idea is to provide a dry coloured fabric, made of plant fibres, compatible with the traditional composite manufacturing processes (hot pressing, autoclave, resin infusion, pultrusion…) having a very wide palette of colours with depth and leaving visible the fabric pattern when embedded in a transparent matrix. The colour is in depth and thus is protected by the used matrix. It can substantially limit the colour modification due to **ageing** effects.



▲ *Figure 16: Coloured woven hemp fabric epoxy composite*

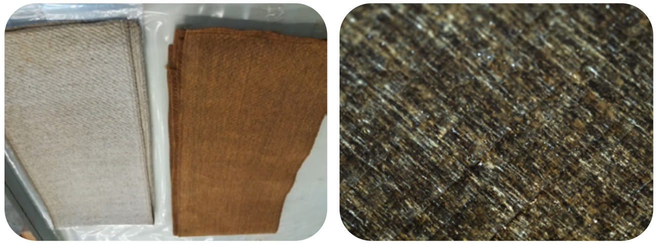
Braided hemp composites

Pipes were also developed from the braided hemp preforms. The low-twisted tenacity of the rovings are sufficient to sustain the solicitations applied during the braiding.

▲ *Figure 17: Braided hemp epoxy composites*

3.2.3. WOVEN HEMP FABRICS REINFORCED FURAN MATRIX COMPOSITES

Some of the hemp fabrics were also impregnated by a furan resin. The PFA (poly(furfuryl alcohol)) used is a thermoset polymer commercialised by Transfurans Chemicals. It represents an interesting polymer since, in addition to being bio-based (obtained from sugar cane bagasse), it has also the main advantage to exhibit good fire-retardant capabilities. It has also some drawbacks, in particular when used with plant fibres, since a large amount of water is released during production. It might slow down the process, lead to porosities and thus adversely affect the overall properties in the final composite. The main challenges related to composite manufacturing with furan and plant fibres concern also the potential acid degradation of fibres and the brittleness of resin. The manufacturing process (B-staging, moisture release times…) was optimized during the SSUCHY project to reduce porosity (below 5%) and obtain a composite **stiffness** similar to theoretical predictions. Despite this optimization, the strain and strain at failure of the obtained composites remain lower the expected and this type of composite is recommended for stiffness-based design applications.



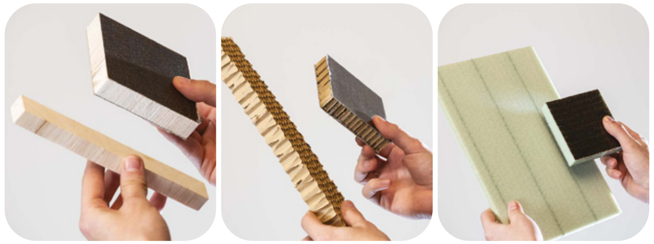
▲ *Figure 18: Woven hemp fabrics before and after preimpregnation with furan. Right: resulting composite*

3.2.4. COMMINGLED HEMP/PA11 COMPOSITES

The impregnation of polymer into the reinforcement is considered as major concern during the fabrication of thermoplastic composites. Indeed, the viscosity for most of the thermoplastic matrices is quite high, which inhibits proper impregnation of the matrix to the reinforcement. Partially impregnated intermediate materials in the form of commingled yarn offer a route for efficient manufacturing of thermoplastic composites due to reduced flow distance. Therefore, intermediate materials known as commingled fabrics were developed within SSUCHY to assist the fabrication of continuous hemp fibre reinforced PA11 thermoplastic composites. These commingled materials offer reduced processing time (consistent with automotive production constraints), the potential for fast, clean and automated manufacturing, as well as infinite shelf life compared to thermoset prepregs. The obtained mechanical properties at composite's scale remain lower than expected due to the high compaction of the hemp fibres within yarns and their limited impregnation with PA11 (https://doi.org/10.3390/coatings11070770[24]). This could be further improved by optimizing the **hybrid yarns** architecture.

3.2.5. SANDWICH COMPOSITES

Various sandwich materials were also developed and characterised using eco-friendly cores such as balsa wood, paper honeycomb, **recycled** PET foam (PhD Thesis Benjamin Sala, Université Franche-Comté, 2021 https://doi.org/10.1016/j.compositesb.2021.109572[25], and bamboo rings https://doi.org/10.1016/j.jcomc.2020.100048[34].



▲ *Figure 19: Pictures of sandwich materials. Skins are made with woven hemp fabrics and GreenPoxy. The core materials are balsa wood, paper honeycomb and recycled PET foam (from left to right)*

3.3. Adding value through enhanced functionalities

3.3.1. IMPROVING THE MOISTURE DURABILITY OF FLAX AND HEMP FIBRE COMPOSITES

Perhaps the main potential weak point of plant fibre composites is that the fibres do absorb substantial amounts of water, which does lower the fibre and composite stiffness by approximately 25% in winter average outdoor humidity (85% RH), but also leads to swelling and shrinking of the fibres inside the composite in respectively humid and dry conditions, which will lead to damage inside the composite over time and reduces the **durability** of these materials. In the SSUCHY project, the material durability was monitored and analysed in various loading conditions (hygrothermal ageing, hygrothermal **creep** and **fatigue)** and various strategies to mitigate the problem were investigated.

Results showed that indeed when bio-fibres are fully dried before production, and subsequently equilibrated at high humidity (80% RH or more), they develop a substantial amount of micro-damage due to fibre swelling. This had at the start of the project lead to the hypothesis that when fibres would be processed in non-dried condition, this should lead to less damage during hygrothermal ageing and thus to better retention of mechanical properties. This was indeed proven during the project. The figure 20 shows that transverse UD composite **strength** is much better retained when the fibres are not dried but pre-conditioned at standard humidity (50%).

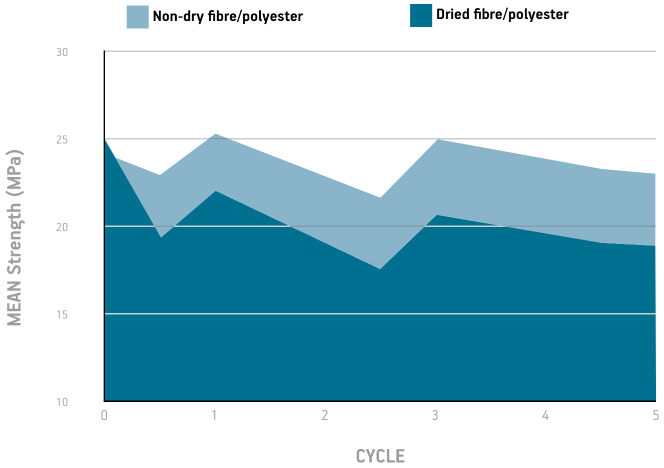
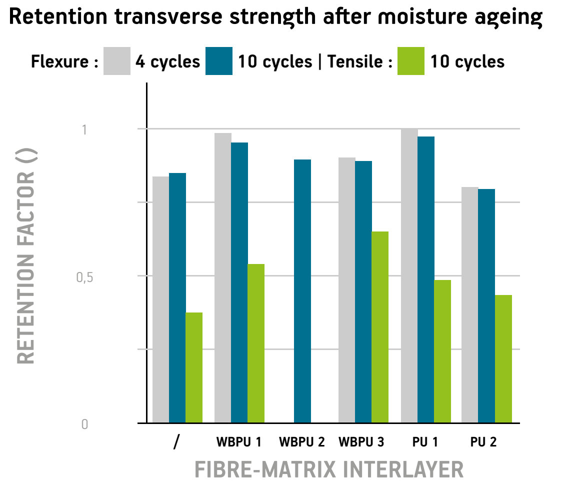


Figure 20: Residual transverse bending strength after moisture cycling, of composite prepared from non-dry fibre (conditioned at 80% RH) versus composite prepared from fully dried fibre; samples tested after re-equilibration to standard conditions (50% RH). Non-dry fibre clearly better maintains its strength.

Not drying the fibres means that first the resin should be able to tolerate water in the fibres and second that during processing no steam is released leading to porosity in the composite. The first aspect was solved in the project by Nouryon for polyester resins by the further development of cobalt-free accelerators which are water tolerant. Two iron and copper based catalysts were launched commercially. The second requirement can be met by tuning the curing peak exotherm or by raising the boiling point of water by employing pressure.

The research on moisture ageing further showed that immersion testing is more predictive of outdoor ageing for uncoated samples, than cyclic moisture testing. Surprisingly, cyclic moisture testing actually lead to improving composite properties beyond a certain amount of cycling, leading to speculation about fibre strengthening mechanisms like hornification or self-healing. Moreover, realistic outdoor conditions were simulated in the lab which indicated that the effect of moisture on fibre stiffness is lower than previously anticipated.

Another route chosen to improve moisture durability was the employment (and synthesis) of an **elastomeric fibre coating.** When the coated fibres are embedded in the polymer matrix, the formed elastomeric interlayer is expected to mitigate hygroscopic stresses, hence, reducing damage development at the fibre-matrix **interface.** As seen in Figure below, results showed a significantly better retention of both transverse and longitudinal properties after wet-dry cycling between RH 32 and 96% at 40°C. Moreover, the fibre coating led to an interesting reduction in water uptake.



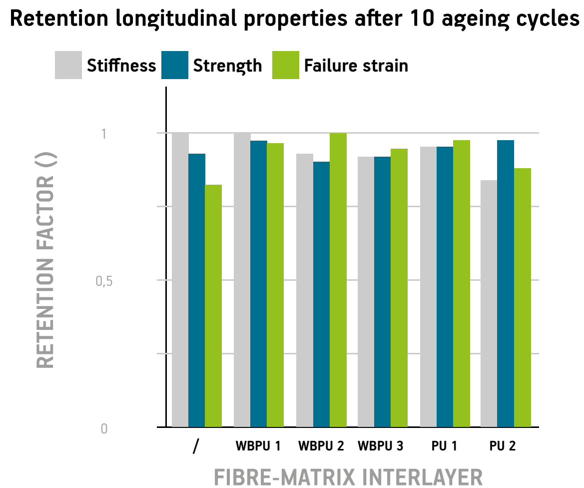


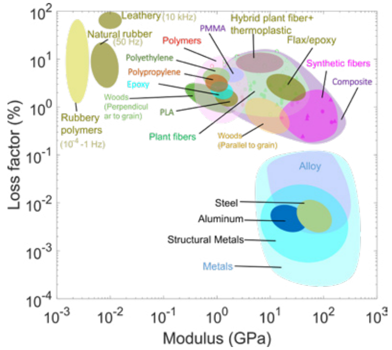
Figure 21: Retention of transverse and longitudinal properties after moisture ageing of flax fibre reinforced epoxy composites having an elastomeric interlayer

Treatment with polycarboxylic acids did not give significant improvements in durability. Fibre-matrix adhesion on hemp fibre was characterized by micro-droplet testing for various polymer matrix systems used in the project (furan, bis-guaiacol, PLA); also contact angle measurements were done.

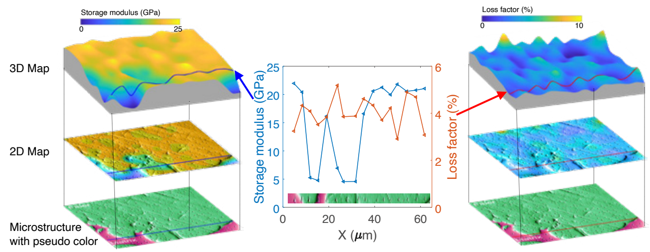
Hygrothermal creep studies were conducted on sandwich constructions as well as on the sandwich skin (DOI: 10.1016/j.compositesa.2020.106204[22]) and core materials (DOI: 10.1016/j.compositesb.2021.109572[25]) separately. Creep at enhanced temperature and humidity was substantially enhanced compared to standard conditions. Water and moisture exposure tests were conducted on panels for the aircraft application.

Finally, a high cycle fatigue study was conducted till 100 million cycles, raising the question if flax and hemp fibre composites perhaps do not show a distinct fatigue limit (DOI: 10.1016/j.compositesb.2019.02.009[32]).

3.3.2. DAMPING PROPERTIES OF BIO-BASED COMPOSITES



A technical challenge to which bio-based composites can strongly contribute is related to vibration and acoustics performance of composite structures. Indeed, the literature clearly notes that the damping capabilities of bio-based composites is generally much higher than that of synthetic fibre composites: the damping ability is measured by the **loss factor** which is typically between 0.7% and 14% for bio-based composites, while the values typically range between 0.24% and 2.5% for synthetic fibre composites. This category of materials hence exhibits a novel compromise between damping and stiffness, which is of first interest for various applications where lower vibration or acoustic levels are expected. The first contribution of the SSUCHY project regarding this topic is a review paper (https://doi.org/10.1016/j.compstruct.2021.114392[27]) with almost 200 references, providing a state-of-the art of the damping properties of bio-based composites, covering methods, analyses and limitations of existing studies. In particular, the understanding of what is happening at the scale of the fibre and how these phenomena are linked to the damping performance at the scale of a structure is a question that is still open. The development of specific techniques at microscale during the project provided new understanding of how the dissipation mechanisms are distributed in the matrix, the fibres and the interface.



With this knowledge, it becomes possible to use multiscale techniques to describe and understand the effective properties of the composite at the structure scale. This was also addressed in the project, both from computational and experimental points of view. Composites to be used as skins and sandwich structures have been considered, with particular attention paid to the components, but also to the environmental effects on the dynamic behaviour of these materials. Indeed, frequency, temperature and humidity are known to have a strong impact on the elastic properties of **bio-based materials,** which is also the case for the damping properties. This was deeply investigated in the project, with a focus on the materials developed by the SSUCHY consortium, and more particularly on some composite skins and sandwich structures that have been identified as promising materials for the demonstrators of the project: from characterization and computations at various scales, the components and multi-layered arrangements dedicated to specific applications where damping plays a major role have been proposed and implemented in the demonstrators.

4 DEMONSTRATION OF THE INNOVATION

In parallel of the work conducted by the academic institutions and in collaboration with some of the companies, SSUCHY has also made some major steps on the development of advanced functionalities at the industrial scale, illustrated through several demonstrators detailed in the following pages.

Regarding the Life-cycle assessment impacts, we can highlight:

- **A high potential** to reduce CO2 footprint of products by using biobased composites (especially during **production,** also for the full life cycle)
- Many environmental benefits, but take care of land use, water depletion, eutrophication, **renewability**

4.1. Hemp: a good candidate to expand purpose-grown biomass for composites reinforcements applications

The objective of SSUCHY was to take advantage of availability, technical and environmental-friendly characteristics and moderate cost of hemp fibres to market a high performance plant fibre reinforcement for composite application with optimal impregnation and competitive price.

In Europe, hemp is currently processed using mechanical systems, based on **beating** and **breaking** rollers, which provide fibres in the form of short and medium-length fibres from disordered straws. This processing method is quite damaging for the fibres and the mean values of their resulting tensile properties are generally in the range from 15 to 35 GPa for the stiffness and 350 to 500 MPa for the strength, depending on the variety, the retting and testing conditions.

In the SSUCHY project, two routes were investigated to produce continuous aligned reinforcements from selected varieties (Futura 75 and Fibror 79) cultivated and processed in Italy and France, using optimized agronomic (sowing and harvesting times…), retting and processing conditions.

More information : Video Ssuchy Hemp Processing

1. **Adaptation and simplification of the flax textile method.** This strategy follows the traditional method to obtain long fibre flax including and use the flax machinery. It requires the use of aligned straws and the scutching and hackling machinery dedicated to flax. The process parameters were successfully adjusted for hemp stems.
2. **Adaptation and improvement of "short-fibre method".** This strategy uses a more economical method to extract hemp fibres in which the most important intermediates were a breaking and carding process. It has the main advantage also not to require aligned stems and then ca be feed by the current hemp straws produced in France and Europe.

In both cases low-twisted rovings suitable for weaving were obtained. Results demonstrate that using the two paths, a well-controlled retting and well-suited processing settings, hemp can achieve properties comparable to high quality long flax fibres for high performance composites, with tensile stiffness between 50 and 60 GPa and tensile strength between 350 and 600 MPa, to be compared to on average 59.8 GPa and 527 MPa previously measured for industrially hackled flax. These primary processing steps were demonstrated at the lab scale but also using industrial machinery by the partner Linificio e Canapificio Nazionale with the production of hemp yarn of 300 tex.

The weavability was further demonstrated at both lab and industrial scales using the low-twisted rovings. Using rovings instead of yarn makes a significant difference when compared to the traditional processing for textile application, and limit time, energy and money consumption.

4.2. Novel curing agent suited for non-dried fibres to improve moisture resistance

Natural fibres such as hemp and flax contain up to 12% of water depending on the RH of the environment. Curing composites that use natural fibres is challenging, if not impossible, when using standard cobalt-based curing systems. Cobalt carboxylates are prone to hydrolysis under the influence of water and then become unreactive for the curing process.

To address this issue, Nouryon, through its Polymer Catalyst unit, produces and develops curing systems, including peroxides and accelerators for room-temperature curing, for polyester based thermosetting resins. More precisely, the company has introduced its range of Nouryact® accelerators, which are not sensitive to water when curing UP resins. This gives an advantage to customers who work in moist conditions and use wet filler materials, such as non-dried natural fibres. Nouryon has also shown that structural composites based on non-dried flax fibres and different grades of UP and vinyl ester (VE) resins can be produced in a vacuum **infusion** process.

For laminates made with non-dried flax fibres, Nouryact proved to result in the same mechanical properties as for dried flax fibres in combination with a traditional curing system.

Discover Nouryon's cure systems for bio-fibre reinforced composites in this video:

Our task in the SSUCHY project was to develop novel curing systems for bio-based resins, which meet labelling requirements and are not water sensitive. Within the four-year project we have developed new combinations of peroxides and metal-based accelerators which are not water sensitive.

Indeed, part of the SSUCHY project was the production of laminates from the produced woven hemp fabrics which were received by Nouryon (balanced satin, approximately 350 g/m^2) for evaluation in cure.

The moisture content in this fibre was measured with a heat balance. The fabric was measured as such and after conditioning for 24 hrs at higher humidity at 20 °C in a glovebox.

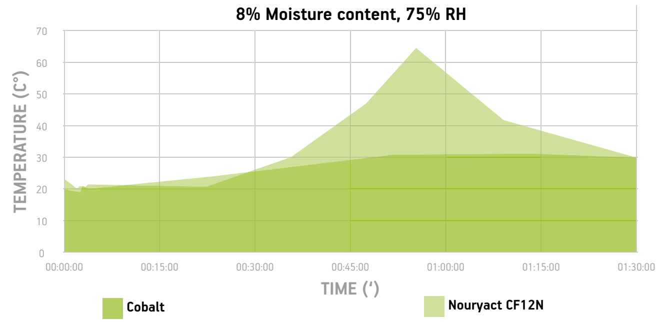
Table 1: Moisture content in hemp fabric

Relative humidity (%)	Water content in fabric (%)
25	4.5
50	6.5
75	8
85	11

If hemp is exposed to 85% RH, moisture content more than doubles compared to dry (<50% RH) environments. Standard laminate (4 mm, 4 hemp fabrics) reactivities were measured in a medium reactive ortho phthalic resin with standard MEKP (Butanox M-50), and Cobalt 1% accelerator (Accelerator NL-49PN) and a Copper based accelerator (Nouryact CF12N) (1,5 phr peroxide/ 1 phr accelerator).

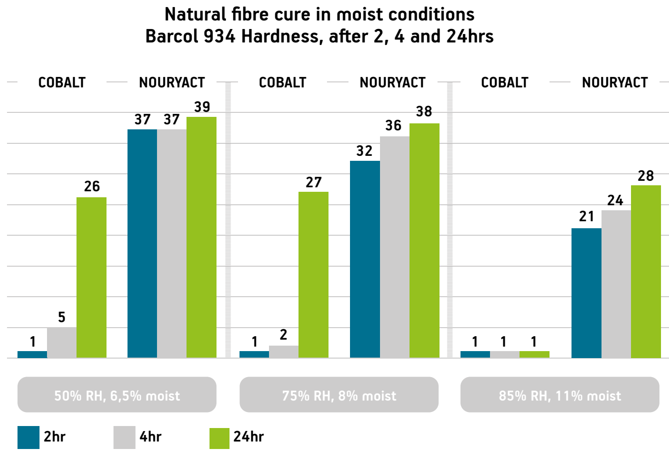
A thermocouple was placed in the middle between the hemp fibre fabrics to measure the time – temperature curve.

See below an example of a time-temperature curve.



Graph 1: time- temperature curve at 50% RH

Laminates were prepared of fabric with 4.5/ 6.5/ 8 and 11% moisture. An important parameter of prepared laminates is the hardness build-up during cure.



Graph 2: hardness build-up during cure at different humidities

So in conclusion, if these fibres are used in highly humid environments, the increased moisture content will result in no cure when using cobalt. When using Nouryact CF12N on the other hand, it can be seen that cure properties and hardness build-up are still good.

4.3. Automotive: floor and trim panel structures for car

TREVES group is an owned company established in 1836, a global automotive Acoustic and trim specialist for Powertrain, Exterior, interior and trunk. The group operates in a logic of vertical integration from raw material to just-in-time delivery, due to its international presence, which allows it to offer a global service to its customers. TREVES is very active in R&D through its global research and development center in Reims.

The mass reduction is a key issue at European level. In fact, union regulations have established binding standards for new car emissions up to 135 g of CO2 (5.2 l / 100 km) per km in 2015 and 95 g of CO2 / km (3, 7 l / 100km) in 2020. This is reflected in particular by an objective of structural reduction in the average weight of vehicles, which should ultimately drop from 1,200 kg to around 900 kg.

In this context, lightweight solutions, with iso-performance, are systematically requested from tier 1 equipment manufacturers, such as the TREVES group. However, its customers are not inclined to pay more for a light solution using recycled and / or biobased materials.

In addition, European Directive 2000/53 / EC relating to End-of-Life Vehicles (ELVs) sets quantified objectives to be achieved by January 1, 2015 at the latest in terms of recycling:

- A minimum rate of reuse and recycling of 85% by weight of ELV
- A minimum rate of reuse and recovery of 95% by weight of ELV

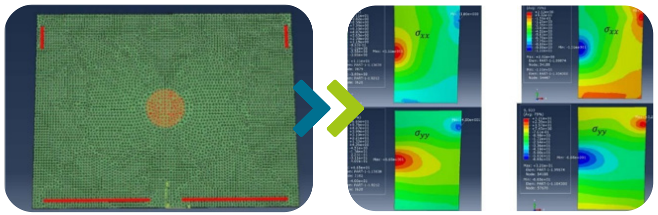
In this configuration, TREVES strives every day to offer products with an optimum weight and try to introduce more and more recycling or renewable material for each application according to the manufacturer's specifications.

That why Treves have decided to participate in SSUCHY Project, to find some solution 100% bio-based for its applications. In addition, to collaborate with innovative European research groups and to bring the completely bio-based composites value chain: from the sourcing of raw materials to the **end of life** of the products via their recyclability.

Due to the short cycle time used in the automotive industry, Treves was very interested to find with the SSUCHY project a thermoplastic binder with the best hemp fibre to compose the reinforcement of its sustainable load floor.

Through the SSUCHY project, Treves was able to investigate different reinforcements and structural cores to achieve the composition of his product by simulation and physically.

Simulation test: ▼



Even if at the present time, there is not a solution that can meet all automotive constraints, especially in terms of cycle time, humidity and price, the SSUCHY project has enabled Treves to work on natural fibres and identify all parameters influencing the performance of his final product, while giving it access to the various players in the field.

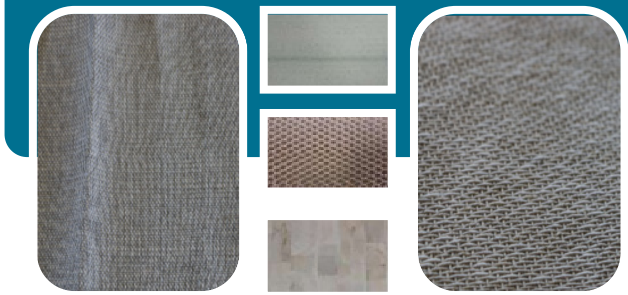
Thanks to the natural fibres, Treves thinks they can make their products more «renewable», and will continue to work on it in order to offer his customers a product with a renewable material rate of 75%.

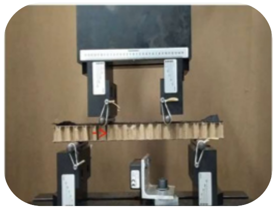
Material tested

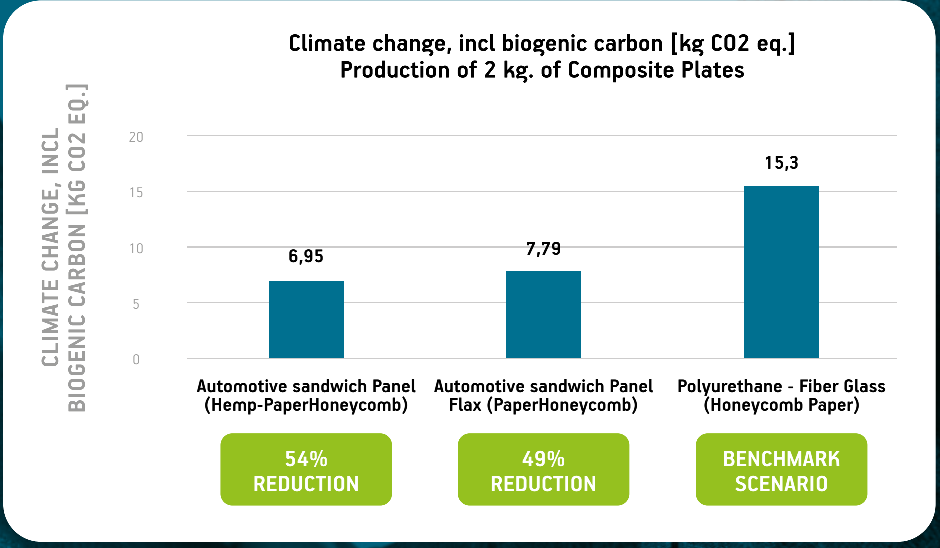
To try to reduce the weight of the complete structure, while trying to meet the requirements, different types of reinforcement and structure have been investigated and tested in an industrial configuration in order to take in account the real life of the automotive industry.

Addition to, different binders were also tested. Unfortunately, the thermoplastic binder (aliphatic polyester) studied in the Ssuchy project did not match with the thermal condition for an automotive application.

The different tests allowed us to see also that some of the configurations were not suited to the automotive industry due to the cycle time or the mechanical perfomances, but could be used for other applications.







LCA conclusions for bio-based floor and trim panel structures for automotive applications:

Production phase:

- Up to 54% reduction on GWP (compared to the benchmark scenario: Polyurethane-Fiberglass-Paper Honeycomb)

Use phase:

- 0.37% reduction on GWP (Considering 5 Kg mass reduction)

End Of Life of phase:

- Concerning GWP: Sanitary Landfill has lower impacts.
- Selection between the options for the EOL scenario needs to be discussed by considering all environmental impact indicators

Full life cycle:

- Up to 1.3% reduction compared to the benchmark scenario

4.4. Aeronautic: cockpit panel for electric aircraft

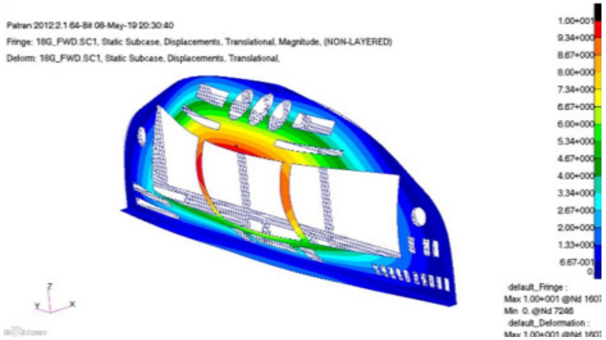
The second application area for the developed bio-based materials is about interior parts of an electric aircraft and more exactly instrument panels. **EADCO Gmbh** has identified area of use for possible applications of environmentally friendly aircraft interiors (mostly sandwich panel structure) based on natural fibres and alternative matrices.

The advantage of possible use of "green material" in a "green aircraft" can represent a worldwide sustainable milestone:

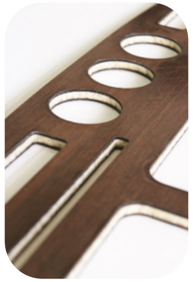
- Further CO2 savings could be achieved at end of the service life due to easier recycling and disposal of the sandwich panels
- Due to the lower environmental impact during the production of natural fibres and thermoplastic matrices, additional environmental benefits, with reduced particle and gas emissions, can be achieved

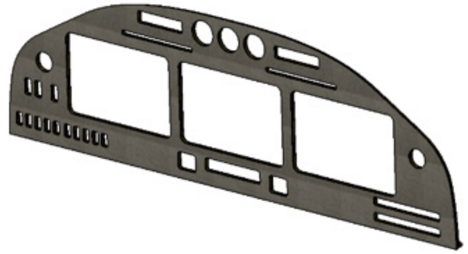
Through SSUCHY project EADCO proposed to substitute the current design carbon/epoxy solutions by a hemp reinforced composites sandwich materials.

The possible applications using bio-based materials and natural fibre reinforcement were investigated for several green aircraft interiors (Sidewalls, Ceilings, Floors, Dashboard Cockpit Panel) and EADCO together with Partners has concentrated the effort on the first ***"Dashboard Cockpit Panel"*** designed for all-electric aircraft.



The strict requirements to fulfil the aircraft specifications and certification rules were the main challenge of this project. The requirements involved:mechanical properties (skin-core bonding, flexural strength, and impact resistance), acoustical properties **(transmission loss),** compliance to cabin environment (vibration, humidity, fluid susceptibility, etc.), Weight and the fire performance have been evaluated and validated through four tests according to the EASA regulations for CS-23 and CS-25 certification (The Test procedures for Self-Extinguishing Materials must be in accordance with the rules stated in the Section 25.853 Appendix F: Flammability, Heat release rate test, Smoke density, Smoke toxicity).





Production of the "Dashboard Cockpit Panel" was achieved using autoclave (separate curing of the skins, laser cut to shape, bonding to foam and curing in vacuum-bag) and the ambitions at the beginning of the project are reflecting the very good results obtained for the engineered and produced Dashboard Cockpit Sandwich Panel with Flax and with Hemp.

Up today, the fire performance tests are still on-going and due to lack of time to produce the test specimen impacted by COVID-19 pandemic, unfortunately we will be not able to complete all the required tests. Nevertheless, the engineering and production activities have been successfully completed in relation to the Aircraft Dashboard demonstrator with Flax and also with Hemp."

Rosario De Luca, *EADCO's CEO*

LCA conclusions on Bio-based sandwich material that fulfills the requirements of aerospace certification

Production phase:

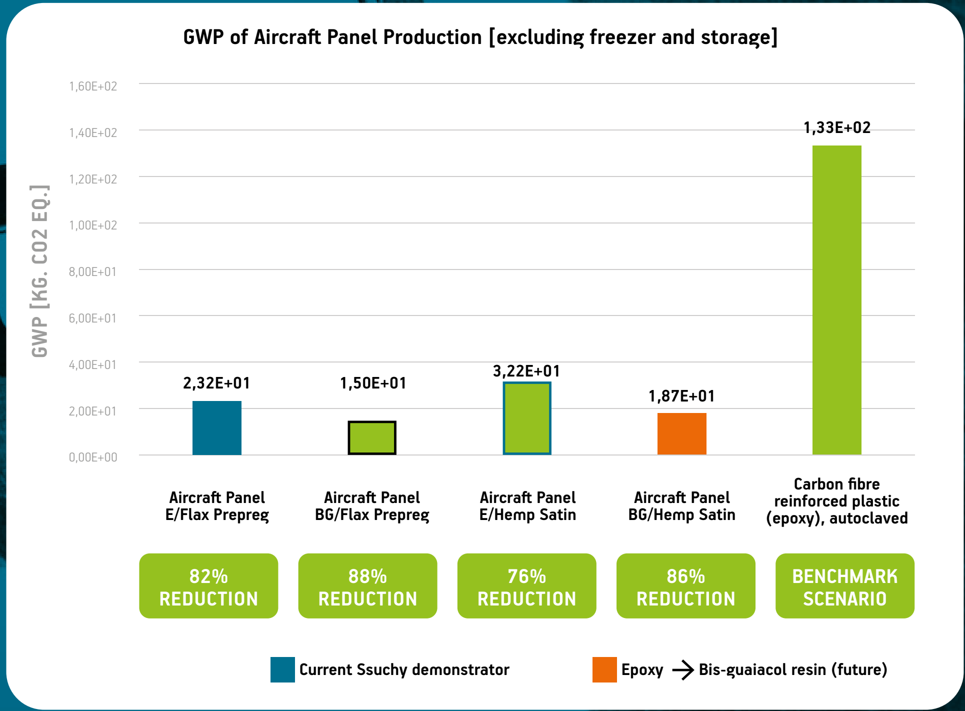
- Up to 88% reduction on GWP (compared to the benchmark scenario: Epoxy-Glass Fiber)

End Of Life of phase:

- Concerning GWP: Sanitary Landfill has lower impacts.
- Selection between the options for the EOL scenario needs to be discussed by considering all environmental impact indicators

Full life cycle:

- Up to 85% reduction compared to the benchmark scenario.



4.5. High performance Green Loudspeaker system

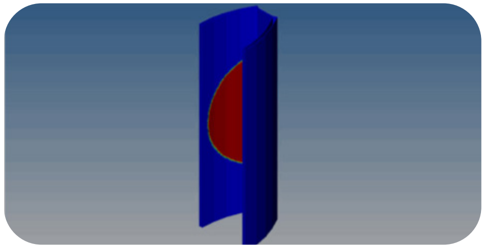
Founded in 1989 Wilson Benesch, remains a family-owned SME operating out of its restored Art Deco building in Sheffield, England. It is a vertically aligned organisation that incorporates research, development and manufacturing to build its products which it then distributes to a well-established global distribution network.

Wilson Benesch has earned a global reputation for its innovation, manufacturing quality and aesthetic design. Amongst many of its achievements, it is perhaps most notably recognised as having introduced a wide range of advanced technology designs and in particular carbon fibre based composite structures. Wilson Benesch has consistently reinvested in modern manufacturing systems and today its expertise in this field is recognised as peerless. In 1994 the company launched the A.C.T. One Loudspeaker - A novel, Modular design incorporating the world's first curved carbon fibre, advanced composite structure. The A.C.T. One disrupted a market that was until then, dominated by the square wooden box. The Modular design will enable the seventh iteration of this design to be launched in 2022. "The Future is Carbon" has been the company's strapline for all these years.

It has always been recognised that the company's achievements have been born not just of its design and innovation, but also its multi-faceted manufacturing capability which is completely integrated both within the company and outside the company, leading to the establishment of a large community of collaborative partners including many academics, scientists and engineers throughout the world.

Within SSUCHY, several research activities contributed to further the knowledge and understand of how different structures behave when subject to acoustic energy.

SSUCHY has indeed provided the possibility to tune the structure of the A.C.T. One loudspeaker, that was not previously possible. The new A.C.T. Monocoque generation developed within SSUCHY manufactured with the SSUCHY hemp satin fabric and composite cores with different biobased and recycled components allows to adjust the resonances of the system by 7% and increasing in baseline damping (+0.5% in raw value). Those numbers are significant for the broadband response of the loudspeaker within a 1 Hz-300 Hz (low frequencies) range. A particular design of the loudspeaker involving a hybrid biobased core configuration developed within SSUCHY also provides an excellent damping of all the upper modes, with very significant equivalent loss factors around 3.3%. Wilson Benesch believes that these new structures should be described as a Next Generation materials science, as they are capable of achieving similar mechanical properties to Oil-based systems, while at the same time delivering significantly superior damping capabilities that were not previously possible.



Moreover, the VRTM (Vacuum assisted Resin Transfer Moulding) technologies developed by the company have already delivered significant reductions in the material costs, material waste and energy consumption required to process the parts. The design of the VARTM process has also been aided via the use of resin transfer moulding simulation tools, like the Fast **RTM** code of iChrome Ltd and the support of the University of Bristol.. The VRTM process developed by WB is able to produce high quality loudspeakers, waiting for less than 10 minutes to obtain the full filling of the loudspeaker through the resin. Wilson Benesch sees that these materials offer clear opportunities for further development and within Wilson Benesch there is already a multitude of new applications being developed. The audio industry is a relatively small market, however the data from this work could lead to many new applications in a multitude of other industries. As the world races to move away from fossil-based materials science to the new Bio-Economy, the work that has been accomplished as a result of SSUCHY will undoubtedly provide a significant contribution towards the goals of sustainable manufacturing and the aims of the Circular Economy.

> Sustainability has been at the forefront of the company's business plan for some years, but as a direct result of the SSUCHY Project, the outcomes can be truly described as transformational. The SSUCHY project team has been able to not only meet the aims and objectives set out in the original Project Plan, but to also go well beyond this to achieve market-ready finished parts (TRL 9) that will enter the market within months of completion of the project.
>
> **Craig Milnes, *Design Director at Wilson Benesch***

LCA conclusions on bio-based composite materials in terms of vibration and acoustics :

Production phase:

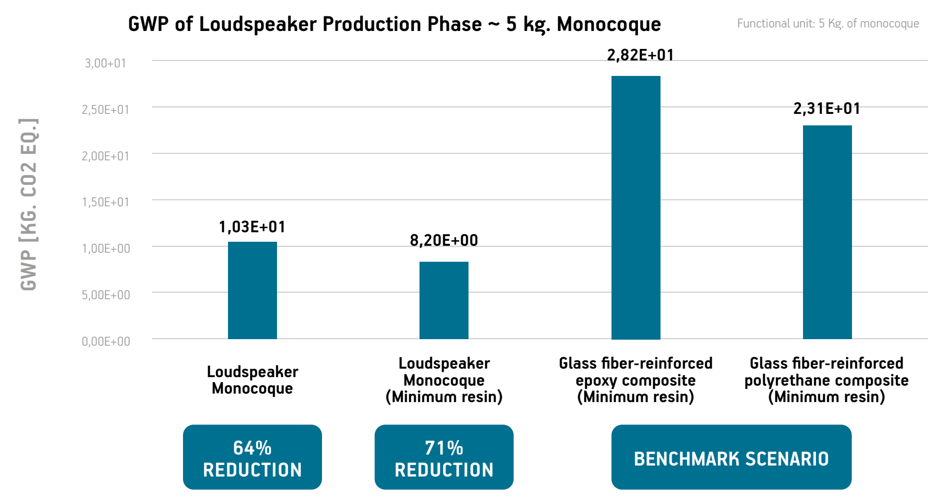
- Up to 71% reduction on GWP (compared to the benchmark scenario: Epoxy-Glass Fiber)

End Of Life of phase:

- Concerning GWP: Sanitary Landfill has lower impacts.
- Selection between the options for the EOL scenario needs to be discussed by considering all environmental impact indicators

Full life cycle:

- Up to 77% reduction compared to the benchmark scenario.



4.6. Transportation: monocoque structure for electric scooter

Since 2014, NPSP develops sustainable, biobased, fibre reinforced plastics for street furniture/infrastructure and mobility. Within SSUCHY, NPSP focused on the biobased scooter body of the electric scooter (see figure 1). The concept of the electric scooter is a large monocoque structure to which the drive train, a large battery pack, the steering construction, the saddle, lights etc are added.

The scooter is a perfect case for testing and demonstrating the use of high end biocomposites in mobility applications. Advantages of these high end biocomposite are on environmental impact, specific strength and stiffness as well as vibration and acoustic damping properties. Unfamiliarity with the material and costs are possible thresholds for getting these materials implemented in the market. SSUCHY is by its set up targeting these issues and demonstrating possible applications.

Figure 1: BEE Electric scooter

The ambition at the beginning of the project was to increasing biobased content of the high end long-fibrous biocomposite material, to characterise this material, and make optimal combinations between fibres, resins and core materials. The re-design is optimised on 1) **biobased content,** 2) **weight** and 3) **costs** which was enabled by these newly developed materials and material combinatons. In the optimised design we have decreased the weight to 13 kg (-59%) and we have increased the biobased content from 30% to 65%. The labour time is estimated to be decreased by 50%. The total cost price is expected to be lowered by 40% bringing it within range of the commercial target price.

The optimised design is implemented in a prototype as a proof of principle. The developed materials and preforms as well as the pre-pregging and balloon blowing techniques can, when successful, also be used for other structures and products.

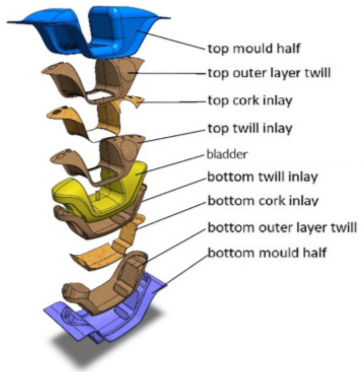


Figure 2: Exploded view of layer build-up of SSUCHY redesign

This spring the scooter will most likely be exhibited at the museum of modern and applied art 'Het Stedelijk Museum' in Amsterdam.

Being partner in the SSUCHY project is a great opportunity for NPSP. It enables us to collaborate with cutting edge European research groups and to bring the whole bio-based composites value chain together: from the sourcing of raw materials to the end of life of the products via their recyclability. All this, keeping in mind to minimize both financial costs and environmental impacts, which are key for the commercial success of NPSP's products.

Within SSUCHY we have greatly gained knowledge on material properties and production techniques. We have developed a demonstrator product with a lighter and/or stiffer, stronger and cheaper biocomposite materials and product(s). Our target now is to get these innovations to the market.

Important issue to raise the biobased content of our biocomposite products is the availability of biobased resins supplied to the market by the chemical industry and whether production companies are able and willing to implement these new resins. We as a company have gained experience within SSUCHY and invest in business development of these new biocomposite materials containing not only natural fibres but also biobased resins and core materials.

Willem Böttger,
co-founder and Director of Innovation at NPSP

Steps to produce the new single part moulded scooter body:

1

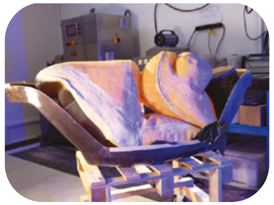
For making the new setup we use the original vacuum infusion mold halves that fit nicely on top of each other.


2

Then we have modified the mould to be able to handle some kind of inner pressure from the bladder. A strong closing solution is key because the rest of the mold shapes are all rounded or spherical and has enough strength and stiffness of itself. On top there will be a connection part for attaching the air pressure for the bladder. For a strong lock normal clamps turn out to be way too flexible and weak. Special steel U-shape clamps were made. After that the mould halves were straightened to fit the uniform clamps.

3

Finally, we had to make a bladder to fit the inner shape of the mold together with the layers of hemp and cork. Therefor we used body parts set to serve as the mold for the bladder.



4

Final result of demonstrator. A monocoque construction out of 1 part.

LCA conclusions for the bio-based monocoque scooter frame

Production phase:

- Up to 60% reduction on GWP (compared to the benchmark scenario: Steel scooter frame)

Use phase:

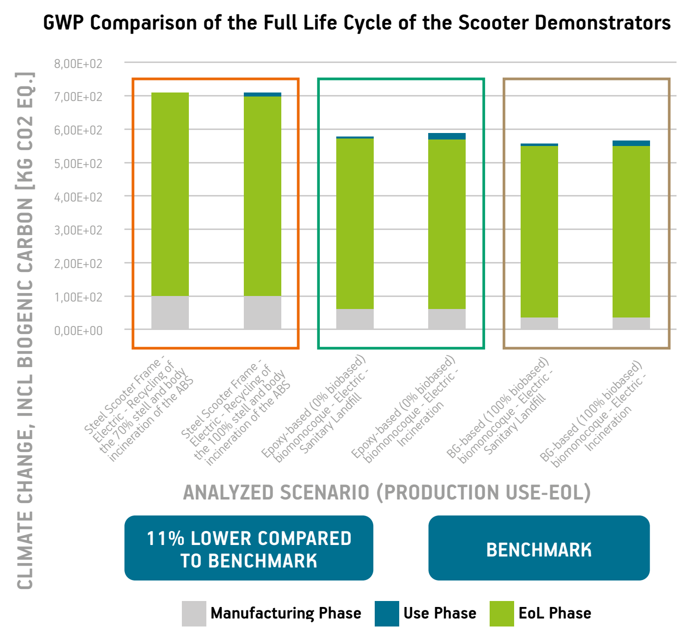
- 16% reduction on GWP (compared to steel scooter - electric.)

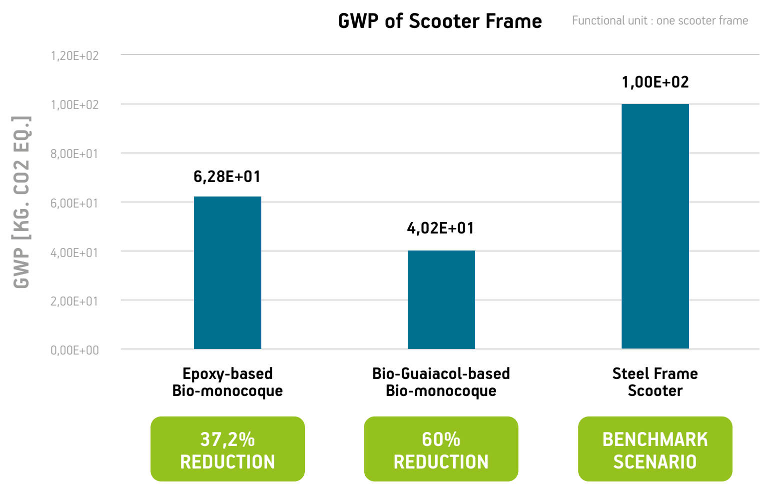
End Of Life of phase:

- Concerning GWP: Sanitary Landfill has lower impacts.
- Selection between the options for the EOL scenario needs to be discussed by considering all environmental impact indicators

Full life cycle:

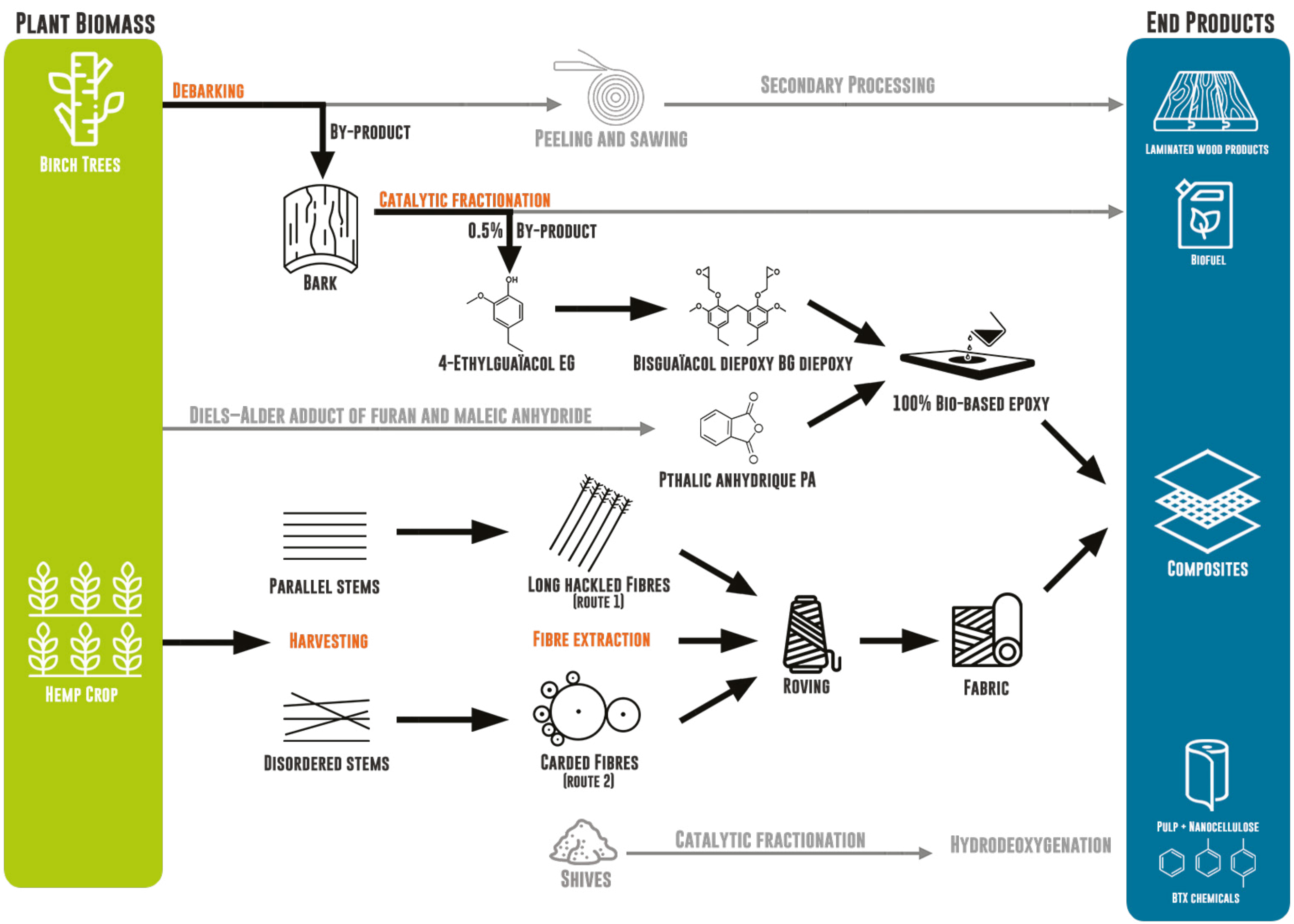
- Up to 11% reduction compared to the benchmark scenario.





5 SSUCHY VALUE CHAIN

Development of structural bio-based composites from a sustainable and economically viable value chain based on plant biomass.



6 EDUCATION

During the 54 months of the project, SSUCHY could demonstrate a real educational impact with 28 students preparing different types of degrees who worked on research axes of work described before but also with the organisation of the first edition of the *"European Summer School on Bio-Based Composites – From plant and wood fibres to advance composites"*.

Key numbers

6
BACHELOR DEGREE STUDENTS

3
ENGINEERING DEGREE STUDENTS

13
MASTER DEGREE STUDENTS

6
PHD STUDENTS

6 PhD Theses

1) Dr. ANNE-CLÉMENCE CORBIN - ENSAIT *(DEFENCE: 10/07/2020)*

During her PhD thesis entitled "Development and multi-scale analysis of hemp reinforcements for biocomposites applications" Dr Anne-Clémence Corbin focused her work on the development of yarns and rovings with sufficient properties for the manufacturing of the reinforcements by weaving technology of which mechanical properties were studied at different scales (e.g. IFBT method). Several characterization tests on the influence of production parameters were performed, allowing to build technical data sheets in order to choose the most appropriate reinforcement for the composite products. Finally, composite plates are manufactured with some of the reinforcements developed, and characterized with tensile tests to compare with other materials already available on the market.

Over these three years, she had the opportunity to work will several of the SSUCHY partners, including the four end-users. Anne-Clémence's work led to the publication of **3** peer-reviewed articles (dx.doi.org/10.1177/0021998320954230[17] ; 10.1080/15440478.2020.1761925[13]; 10.1016/j.compositesb.2019.107582[16]), **5** oral presentation followed by **2** conference proceedings papers and **1** poster in international conference.

Working within the frame of an EU project allows to gather ideas and skills from several countries which is enriching both professionally and personally. After my thesis, I wanted to continue to develop new composite materials with high added value. I am now working in protective composite materials in industry with a lot of European and non-European people and company, and this diversity of culture is very important for me.

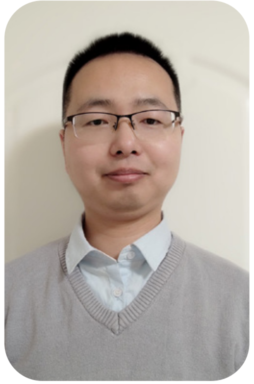
2) Dr. MARIE GRÉGOIRE - ENIT *(DEFENCE: 15/01/2021)*

The thesis work of Dr. Marie Grégoire focused on developing or adapting different hemp fibre extraction techniques in order to obtain a material suitable for use in load bearing composite materials. The first part of this thesis focuses on the use of an "all-fibre" device for the extraction of hemp fibres and the results obtained show a significant decrease in the mechanical properties of the fibres compared to the initial material. Thus, another device was tested which is machine for extraction by scutching/hackling initially intended for flax. The results obtained at the laboratory showed the great potential of hemp fibres: they retained high mechanical properties and lengths. Fibre yields significantly higher than those currently obtained industrially have been achieved. Finally, she studied the level of fineness obtained at the end of processing: various test parameters were investigated in order to know if the treatment really acts via microwave radiation or via the induced temperature.

Marie's work led to the publication of **3** peer-reviewed articles https://doi.org/10.1016/j.indcrop.2021.114045[10] ; https://doi.org/10.1007/s42452-019-1332-4[18] ; https://doi.org/10.1016/j.indcrop.2021.113337[9]) and **4** oral presentations in international conferences.

I feel very pride for having been able to participate in an important European project for the future of biosourced composite materials. It allows us to work in collaboration with other research laboratories, and the presence of industrial partners also makes it possible to see the results of our research applied, which is motivating to continue! I would like to continue working on plant fibres and this has reinforced my plan to stay in academia and become associate professor. While waiting for a position, I am a post-doctoral fellow.

3) Dr. TAIQU LIU - UNIVERSITÉ FRANCHE-COMTÉ *(DEFENCE: 20/01/2021)*



The PhD thesis of Dr. Taiqu Liu aims at contributing to a better understanding of the damping behaviour of Plant Fibre Composites through a multi-scale damping characterization. The influences of many parameters including matrix types, fibre architecture, woven pattern, temperature, frequency and moisture content on the damping properties of PFCs are investigated based on dynamic mechanical analysis (DMA) and modal analysis. Furthermore, a constant amplitude method as well as constant stiffness method are used to map the in situ damping properties at the microscale based on grid dynamic Nanoindentation. These results are then compared to those obtained from dynamic mechanical analysis and modal test methods. The results from dynamic Nanoindentation show the contribution of each component (fibre, matrix and interface) on energy dissipation.

Taiqu Liu's work led to 1 review and 1 peer-reviewed articles ((https://doi.org/10.1016/j.compstruct.2021.114392[27]) ; submitted) and 2 oral presentations in an international conference. He is now working as Associate Professor at Jiangsu Normal University (China).

The opportunity to work in SSUCHY have broadened my horizon and aroused my interest in research. I quite enjoy the cooperation and communication in SSUCHY project. Working in SSUCHY made me realize that humans can do more to lessen their impact on the environment. Finally, I hope my research can make a little positive impact on the future.

4) Dr. BENJAMIN SALA – UNIVERSITÉ FRANCHE-COMTÉ *(DEFENCE: 26/11/2021)*

The objective of the thesis of Dr. Benjamin Sala is to characterize and model the creep behaviour of biobased sandwich structures under different hygrothermal conditions. The methodology used in this work aims to develop a tool for the reliable prediction of the behaviour of sandwich materials, based on the mechanical characterization at the scale of its constituents, and this, under ambient and severe hygrothermal conditions. At the scale of the sandwich material, this work shows that it is possible to develop a biobased material with elastic mechanical performances that can compete with those of a usual petroleum-based solution, while guaranteeing a lower mass and environmental impact. However, one of the limitations of these materials is the exhibition of significant time delayed strains under creep stress. The collected results also show that, although the behaviour and the mechanical properties are very scattered at the scale of the plant fibres, the variability at the scale of the sandwich and its components is significantly lower and comparable to that measured for traditional composites. All the results and tools developed in this thesis will contribute to a more precise design and sizing of biobased sandwich structures in the future.

So far, Benjamin's work led to the publication of **3** peer-reviewed articles (dx.doi.org/10.1177/0021998320954230[17] ; doi.org/10.1016/j.compositesa.2020.106204[22] ; doi.org/10.1016/j.compositesb.2021.109572[25]), **1** conference proceedings and **3** oral presentations in international conferences.

It was a real pleasure to work with the actors of the SSUCHY project. The project meetings were always a pleasant moment of knowledge sharing and allowing to know researchers at the forefront of their field. This thesis work gave me the desire to continue working in the field of bio-based composites in order to make these materials an industrial reality. Indeed, I am currently working as a post-doc with the University of Franche-Comté and MaHyTec company in order to continue the work initiated on these materials.

5) ING. GILLES KOOLEN - KU LEUVEN *(DEFENCE: 2022)*

The aim of the PhD research conducted by Ing. Gilles Koolen was to reduce the moisture sensitivity of plant fibre reinforced polymer composites. Several fibre treatments were evaluated of which an elastomeric fibre coating proved to be the most effective.

Gilles will defend his PhD in early 2022 and his work will lead to several publications that are currently under preparation. He has already contributed to **1** peer-reviewed article (submitted), published **1** conference proceeding (10.1016/j.matpr.2020.01.183[28]) and participated in international conferences with 2 oral presentations.

I really enjoyed to be part of the SSUCHY project. While a PhD subject is typically quite narrow, the diversity provided by a project like SSUCHY, covering a complete value chain allowed me to develop a broad knowledge of the bio-based industry which will definitely help in my future career. I am sure that I will continue to work with sustainable materials and processes. Either in an industrial context or through valorisation of research results. I am eager to gain business management skills and to grow towards a function which combines innovation with commercial interests and project management.

6) Dr. MARIA MORISSA LU - KU LEUVEN *(DEFENCE: 10/03/2022)*

Dr. Maria Morissa Lu started her PhD in KU Leuven in 2016 focusing her research on improving the moisture durability of natural fibre composites by using non-dry fibre. The use of non-dry fibre and resins with low sensitivity to moisture limits the moisture sorption of composites, slowing degradation, thereby improving moisture durability. Maria is about to defend her PhD in early 2022 and has already published 2 peer-reviewed articles (10.1016/j.compositesa.2019.05.029[29] ; https://doi.org/10.1016/j.compositesb.2021.109538[30]), 1 conference proceedings (https://doi.org/10.1016/j.matpr.2019.11.061[31]) as well as 3 oral presentations in international conferences.

Being part of the SSUCHY project has been an extraordinary experience for me. From living in my humble hometown in Gubat, Sorsogon, Philippines, I was able to travel around Europe as I attended conferences and project meetings where I was able to engage in intelligent and lively discussions with experts in the field. Returning to the Philippines, I carry with me the knowledge I hope to share with many as I continue to teach at the University of the Philippines Los Banos (UPLB) to contribute to strengthening education and research in materials engineering.

7 VALORIZATION

7.1. Online communications

A. THE IMPACT OF SOCIAL NETWORKS

The key figures show the impact of the srong presence of the SSUCHY project on social networks where it broadcasted its news and results and established new contacts.

A COMMUNITY OF
433
FOLLOWERS

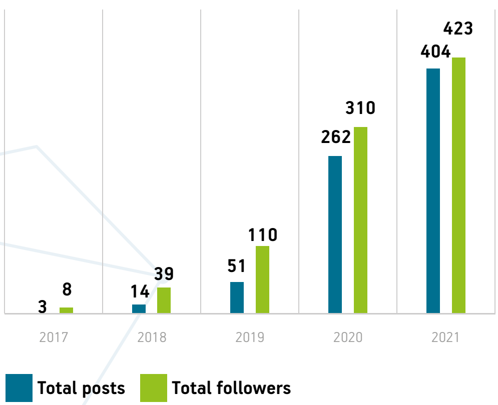
A COMMUNITY OF
417
FOLLOWERS

4 years of constant growth in activity and followers

Each year of the project, SSUCHY has grown its community and activity online

+ 5,3 k % increase of followers

+ 13,5 k % increase of publications



B. THE WEBSITE: A GROWING INFLUENCE

SSUCHY's website has been a showcase for the project to share its activity and results with an international audience.

50 news published (website)

3,500 international visitors

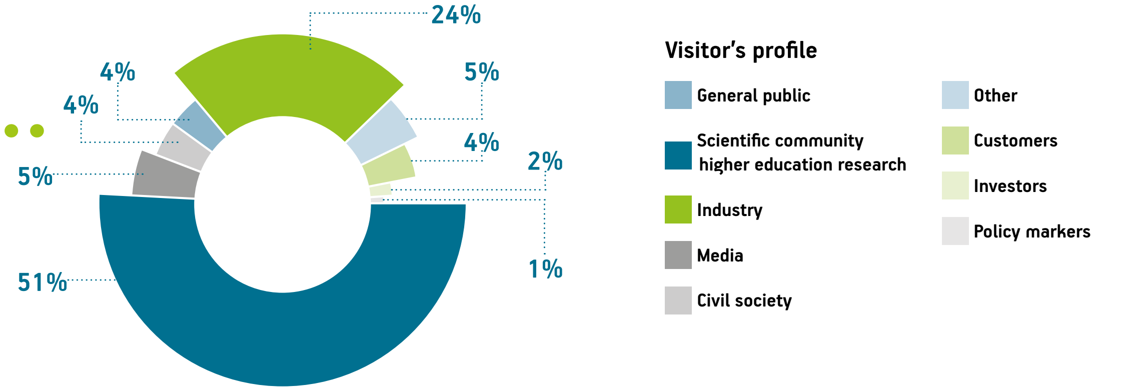
Who are SSUCHY's website visitors?

An 8-month period study (July 2020-February 2021)

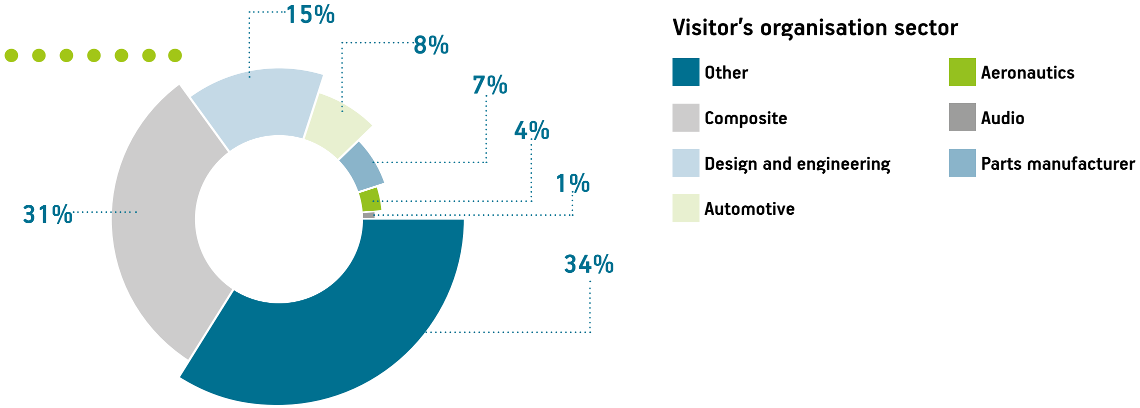
Thanks to a pop-up questionnaire on our website, we have been able to know more about our audience and to learn who they were and why and how they came visiting our project's website.

Overall, 80% of the public that heard about SSUCHY did not hear about it from a person linked to the project, demonstrating that well-established and focused communication on websites and social networks helps to raise awareness of the project outside of its primary community.

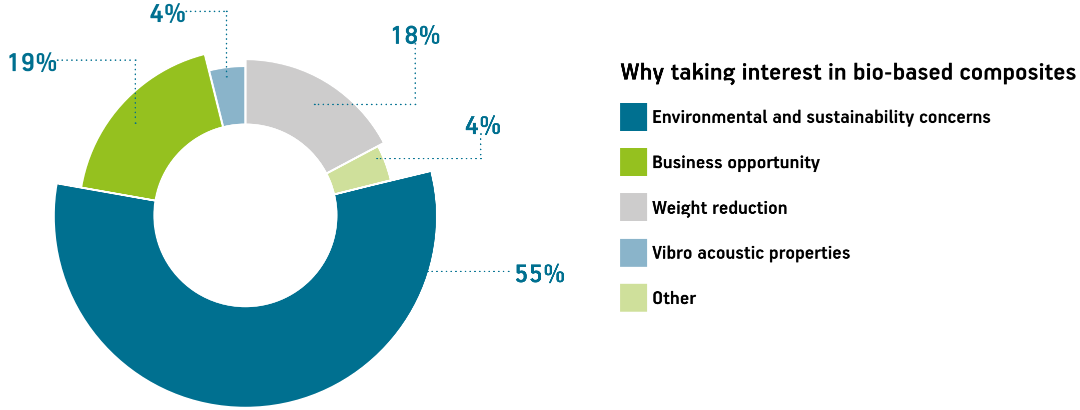
One of the first information we collected focused on **the visitors profile.** We observed a special interest from the "Scientific community" which represent half of our visitors, followed by the "Industry", both making up around 3 out of 4 visitors of our website. Interestingly, there was a strong interest of people close to the SSUCHY project, both in research and industry which represents the core of SSUCHY's stakeholders!



The second information we collected dealt with **the research or business sector.** We noticed the importance of the composites industry which represented a third of our visitors, reflecting the interest of this industry sector in the development of the project that concerns them. In addition, we can mention that not only those involved in the design and transformation process, but also the final beneficiary industries of these innovations are part of our visitors such as automotive, aeronautics and parts manufacturers. Finally, it is worth mentioning that within the "Others" group, professionals from the start of the value chain, farmers being the main visitors. We interpreted it as good news and possibly a nice indicator reflecting the comprehensive side of the website.



If we look at **the "why" behind their interest** in the world of bio-based composites, the predominant interest is in the environmental and sustainability possibilities they can offer, demonstrating the visitors' consideration for such concerns. We also noticed interest in technical advantages they can provide, such as weight reduction or enhanced acoustic properties.



Finally, the positions held by the visitors in their respective jobs ranged from junior to senior management, including owners, as well as students from different universities. This indicates that the development and impacts of SSUCHY are of importance to a wide variety of professionals.

C. THE PRESS IS TALKING ABOUT US

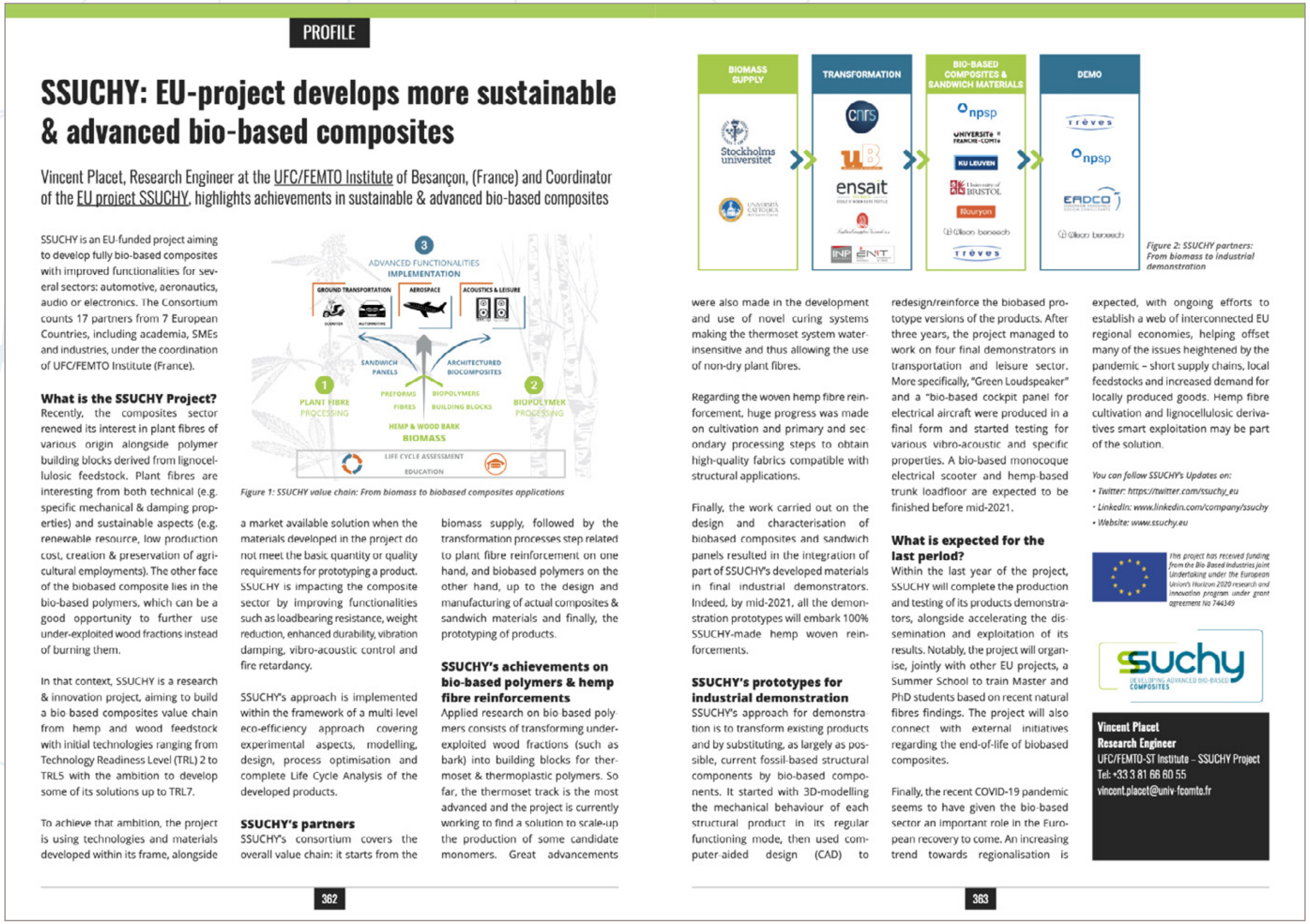
6 Press releases

32 Press articles

Highlight: SSUCHY presented in Open Access Government

Open Access Government is a digital publication of about 200 000 Public and Private sector readership that provides an in-depth perspective on key public policy areas from all around the world, committed to delivering up-to-date analysis, news and exclusive features for a public and private sector readership.

SSUCHY's article (published first and in paper in January 2021) and was the occasion to look back at the project context when it started in 2017, wrap-up its most recent outcomes and have a glimpse to what is expected by its closure in 2021.



PROFILE

SSUCHY: EU-project develops more sustainable & advanced bio-based composites

Vincent Placet, Research Engineer at the UFC/FEMTO Institute of Besançon, (France) and Coordinator of the EU project SSUCHY, highlights achievements in sustainable & advanced bio-based composites

SSUCHY is an EU-funded project aiming to develop fully bio-based composites with improved functionalities for several sectors: automotive, aeronautics, audio or electronics. The Consortium counts 17 partners from 7 European Countries, including academia, SMEs and industries, under the coordination of UFC/FEMTO Institute (France).

What is the SSUCHY Project?
Recently, the composites sector renewed its interest in plant fibres of various origin alongside polymer building blocks derived from lignocellulosic feedstock. Plant fibres are interesting from both technical (e.g. specific mechanical & damping properties) and sustainable aspects (e.g. renewable resource, low production cost, creation & preservation of agricultural employments). The other face of the biobased composite lies in the bio-based polymers, which can be a good opportunity to further use under-exploited wood fractions instead of burning them.

In that context, SSUCHY is a research & innovation project, aiming to build a bio based composites value chain from hemp and wood feedstock with initial technologies ranging from Technology Readiness Level (TRL) 2 to TRL5 with the ambition to develop some of its solutions up to TRL7.

To achieve that ambition, the project is using technologies and materials developed within its frame, alongside a market available solution when the materials developed in the project do not meet the basic quantity or quality requirements for prototyping a product. SSUCHY is impacting the composite sector by improving functionalities such as loadbearing resistance, weight reduction, enhanced durability, vibration damping, vibro-acoustic control and fire retardancy.

SSUCHY's approach is implemented within the framework of a multi level eco-efficiency approach covering experimental aspects, modelling, design, process optimisation and complete Life Cycle Analysis of the developed products.

Figure 1: SSUCHY value chain: From biomass to biobased composites applications

SSUCHY's partners
SSUCHY's consortium covers the overall value chain: it starts from the biomass supply, followed by the transformation processes step related to plant fibre reinforcement on one hand, and biobased polymers on the other hand, up to the design and manufacturing of actual composites & sandwich materials and finally, the prototyping of products.

SSUCHY's achievements on bio-based polymers & hemp fibre reinforcements
Applied research on bio based polymers consists of transforming under-exploited wood fractions (such as bark) into building blocks for thermoset & thermoplastic polymers. So far, the thermoset track is the most advanced and the project is currently working to find a solution to scale-up the production of some candidate monomers. Great advancements were also made in the development and use of novel curing systems making the thermoset system water-insensitive and thus allowing the use of non-dry plant fibres.

Regarding the woven hemp fibre reinforcement, huge progress was made on cultivation and primary and secondary processing steps to obtain high-quality fabrics compatible with structural applications.

Finally, the work carried out on the design and characterisation of biobased composites and sandwich panels resulted in the integration of part of SSUCHY's developed materials in final industrial demonstrators. Indeed, by mid-2021, all the demonstration prototypes will embark 100% SSUCHY-made hemp woven reinforcements.

SSUCHY's prototypes for industrial demonstration
SSUCHY's approach for demonstration is to transform existing products and by substituting, as largely as possible, current fossil-based structural components by bio-based components. It started with 3D-modelling the mechanical behaviour of each structural product in its regular functioning mode, then used computer-aided design (CAD) to redesign/reinforce the biobased prototype versions of the products. After three years, the project managed to work on four final demonstrators in transportation and leisure sector. More specifically, "Green Loudspeaker" and a "bio-based cockpit panel for electrical aircraft were produced in a final form and started testing for various vibro-acoustic and specific properties. A bio-based monocoque electrical scooter and hemp-based trunk loadfloor are expected to be finished before mid-2021.

What is expected for the last period?
Within the last year of the project, SSUCHY will complete the production and testing of its products demonstrators, alongside accelerating the dissemination and exploitation of its results. Notably, the project will organise, jointly with other EU projects, a Summer School to train Master and PhD students based on recent natural fibres findings. The project will also connect with external initiatives regarding the end-of-life of biobased composites.

Finally, the recent COVID-19 pandemic seems to have given the bio-based sector an important role in the European recovery to come. An increasing trend towards regionalisation is expected, with ongoing efforts to establish a web of interconnected EU regional economies, helping offset many of the issues heightened by the pandemic – short supply chains, local feedstocks and increased demand for locally produced goods. Hemp fibre cultivation and lignocellulosic derivatives smart exploitation may be part of the solution.

Figure 2: SSUCHY partners: From biomass to industrial demonstration

You can follow SSUCHY's Updates on:
- *Twitter: https://twitter.com/ssuchy_eu*
- *LinkedIn: www.linkedin.com/company/ssuchy*
- *Website: www.ssuchy.eu*

This project has received funding from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No 744349

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362 363

7.2. Scientific publications

SSUCHY's partners have regularly published scientific articles on main journals with high impact factors. The topics of the scientific articles were mainly about hemp fibres properties and processing, mechanical properties, biomass fractionation, **life cycle assessment,** durability, damping behaviour, biobased epoxy matrix and composite applications.

33 scientific publications published including 23 peer-reviewed articles, 1 review, 7 conference proceedings and 1 short communication (see section 8. References)

10 high impact journals

1 patent

SEVEN HIGHLIGHTS

COMPARING FLAX AND HEMP FIBRES YIELD AND MECHANICAL PROPERTIES AFTER SCUTCHING/HACKLING PROCESSING

Authors: *Marie Gregoire, Mahadev Bar, Emmanuel De Luycker, Salvatore Musio, Stefano Amaducci, Xavier Gabrion, Vincent Placet, Pierre Ouagne*

SSUCHY Partners: *ENIT, UFC, UCSC*

Abstract:

Increasing the production of high-performance natural fibres that minimise their impact on the environment is a challenge that flax (Linum usitatissinum L.) cannot address alone. In flax traditional production territories, hemp (Cannabis sativa L.) can be a complementary source of high added value fibres if their yield of long line fibres can be maximised to levels equivalent to the one of flax. The objective of the present work was to establish process parameters maximising the long line fibre yield using flax dedicated scutching and hackling devices. A lab-scale scutching/hackling device was used to establish sets of process parameters which best improve the long fibre scutching yield and as a consequence minimise the production of tow fibres. Decreases in straw processing transfer and beating speeds during scutching were necessary so that to be less aggressive on the straw and fibres. Very high long fibre yields were obtained after scutching and hackling at the laboratory scale (18 % of the hemp straw mass). These very high results, combined to high straw yield production in the field indicate that hemp can be a very productive source of high-performance fibres as these ones showed tensile properties completely suitable for a textile use as well as for load bearing composite materials. If the potential of high production yields and high mechanical and morphological properties was demonstrated at the lab-scale, this one should be improved at the industrial scale. Suggestions to reach this goal are provided to prevent too high transformation of long fibres into tows and to keep the mechanical potential maximum. When using optimised parameters and a lab-scale scutching/hackling device, it was demonstrated that hemp has the potential for providing equivalent amounts of long fibres per hectare than flax with tensile properties about 20 % lower than the ones of flax.

HOLISTIC VALORIZATION OF HEMP THROUGH REDUCTIVE CATALYTIC FRACTIONATION

Authors: *Suthawan Muangmeesri, Ning Li, Dimitrios Georgouvelas, Pierre Ouagne, Vincent Placet, Aji P. Mathew, and Joseph S. M. Samec*

SSUCHY Partners: *SU, ENIT, UFC*

Abstract:

Despite the increased use of hemp fibre, negligible attention has been given to upgrade the hemp hurd, which constitutes up to 70 wt % of the hemp stalk and is currently considered a low-value byproduct. In this work, valorization of hemp hurd was performed by reductive catalytic fractionation (RCF) in the presence of a metal catalyst. We found an unexpectedly high yield of monophenolic compounds (38.3 wt %) corresponding to above 95% of the theoretical maximum yield. The high yield is explained by both a thin cell wall and high S-lignin content. In addition, organosolv pulping was performed to generate a pulp that was bleached to produce dissolving-grade pulp suitable for textile fibre production (viscosity, 898 mL/g; ISO-brightness, 90.2%) and nanocellulose. Thus, we have demonstrated a novel value chain from a low-value side stream of hemp fibre manufacture that has the potential to increase textile fibre production with 100% yield and also give bio-oil for green chemicals.

NEW ECO-FRIENDLY SYNTHESIZED THERMOSETS FROM ISOEUGENOL-BASED EPOXY RESINS

Authors: *Quentin Ruiz, Sylvie Pourchet, Vincent Placet, Laurent Plasseraud and Gilles Boni*

SSUCHY Partners: *UB, UFC*

Abstract:

Abstract: Epoxy resin plays a key role in composite matrices and DGEBA is the major precursor used. With the aim of favouring the use of bio resources, epoxy resins can be prepared from lignin. In particular, diglycidyl ether of isoeugenol derivatives are good candidates for the replacement of DGEBA. This article presents an effective and eco-friendly way to prepare epoxy resin derived from isoeugenol (BioIgenox), making its upscale possible. BioIgenox has been totally characterized by NMR, FTIR, MS and elemental analyses. Curing of BioIgenox and camphoric anhydride with varying epoxide function/anhydride molar ratios has allowed determining an optimum ratio near 1/0.9 based on DMA and DSC analyses and swelling behaviours. This thermoset exhibits a Tg measured by DMA of 165°C, a tensile storage modulus at 40°C of 2.2 GPa and mean 3-point bending stiffness, strength and strain at failure of 3.2 GPa, 120 MPa and 6.6%, respectively. Transposed to BioIgenox/hexahydrophtalic anhydride, this optimized formulation gives a thermoset with a Tg determined by DMA of 140°C and a storage modulus at 40°C of 2.6 GPa. The thermal and mechanical properties of these two thermosets are consistent with their use as matrices for structural or semi-structural composites.

TOWARDS HEMP FABRICS FOR HIGH-PERFORMANCE COMPOSITES : INFLUENCE OF WEAVE PATTERN AND FEATURES

Authors: *Anne-Clémence Corbin, Damien Soulat, Manuela Ferreira, Ahmad-Rashed Labanieh, Xavier Gabrion, Pierrick Malecot, Vincent Placet*

SSUCHY Partners: *ENSAIT, UFC (LCN aknowledgments)*

Abstract:

Recent developments in the field of bio-based composite materials are mainly focused on the use of unidirectional reinforcements. The production of woven fabrics and required yarns or rovings isstill complex for composite applications due to the finite length of plant fibres and to the high number of process parameters which can be tuned. This study focused on the influence of weave pattern and process parameters on the resulting material properties at different scales. Results from mechanical characterizations and X-ray nanotomography show that very competitive tensile properties can be obtained for woven hemp fabric composites made from low-twisted rovings, in particular when compared to the front-runner flax cross-ply laminate.

IMPROVING MOISTURE DURABILITY OF FLAX FIBRE COMPOSITES BY USING NON-DRY FIBRES

Authors: *Lu Maria Morissa, Van Vuure Aart Willem*

SSUCHY Partners: *KUL*

Abstract:

Non-dry flax fibre and polyester resin that has low sensitivity to moisture were used in the production of composites and the effects on flexural and moisture sorption properties of composites under wet-dry cycling were determined. Results showed that composites made of non-dry fibre have lower moisture sorption and degree of swelling and shrinking compared to composites made of dried fibre. Mean strength and modulus of composites made of non-dry fibre are 4–12% and 13–14% respectively, higher than composites made of dried fibre in longitudinal direction. Mean strength and modulus of composites made of non-dry fibre are 18–22% and 11–21% respectively, higher than composites made of dried fibre in transverse direction after the wet-dry cycling. The results suggest that composites made of non-dry fibre could be used for enhancing moisture durability of composites and lessen the time, cost and embodied energy to produce the composites, by omitting the step of drying the fibres.

EFFECT OF HYGROTHERMAL AGEING ON THE SHEAR CREEP BEHAVIOUR OF ECO-FRIENDLY SANDWICH CORES

Authors: *Benjamin Sala, Xavier Gabrion, Thomas Jeannin, Frédérique Trivaudey, Violaine Guicheret-Retel, Fabrizio Scarpa, Vincent Placet*

SSUCHY Partners: *UFC, UoB*

Abstract:

The development of sustainable sandwich materials is needed in the transportation sector to address environmental concerns related to the production and operation of vehicles. In addition to biobased composite skins, alternatives to classic synthetic core materials must be found to reduce the ecological footprint of whole sandwich-structured composites. This study focused on three eco-friendly lightweight core materials: balsa wood, paper honeycomb, and recycled PET foam. The effect of the hygrothermal ageing on their shear creep/recovery behaviour has been here investigated. Two different environmental conditions were tested: 23 °C-50% RH and 70 °C-65% RH. The results indicate that the maximum shear strain, the time-delayed strain and the residual strain increase for the three core materials with the severity of the hygrothermal conditions. This was attributed to the softening of the constitutive polymeric materials of the cell walls at temperatures close to 70 °C. The balsa wood exhibits the best creep resistance under the two environmental conditions. The identification of the viscoelastic properties highlights that the release times and the shear viscous parameters of the balsa wood and the PET foam depend on the stress level and the hygrothermal conditions.

DAMPING BEHAVIOR OF PLANT FIBRE COMPOSITES : A REVIEW

Authors: *Taiqu Liu, Pauline Butaud, Vincent Placet, Morvan Ouisse*

SSUCHY Partners: *UFC*

Abstract:

This paper reviews the damping characteristics of plant fibre composites (PFCs) with particular attention regarding their performance with respect to that of synthetic fibre composites (SFCs). Indeed, PFCs have become increasingly popular in many application fields. Their specific characteristics when compared to those of synthetic fibres, such as glass fibres, make them good candidates to improve the damping behavior of composite materials and structures. The influences of mesoscale and microscale parameters as well as surrounding conditions are reviewed in the present paper. Contradictory reports are sometimes found, and the existing knowledge on the damping behavior of PFCs is sometimes deficient or ambiguous. Some key points, such as the variability, hierarchical aspects and sensitivity of mechanical properties, are thus discussed. This review provides a first reference for the factors that affect damping properties in PFCs to be used in engineering applications in various fields, including automotive parts, aerospace components, and musical instruments. It also highlights the current shortcomings of knowledge on the damping of PFCs. The Ashby diagram presented here, built from data available in the literature, constitutes a first tool for selecting materials considering the compromise between the loss factor and stiffness for engineering design considerations.

7.3. Events: an expertise solicited abroad

Skills and experience of SSUCHY's partners make its representatives recognized specialists and regularly requested to bring their vision and expertise in conferences and external events.

46 conferences

10 international countries

THREE HIGHLIGHTS

ICNF 2021 5th International Conference on Natural Fibers Materials of the Future

ICNF 2021 - 5TH INTERNATIONAL CONFERENCE ON NATURAL FIBRES, FUNCHAL, PORTUGAL

Key figures:

17-19 May 2021

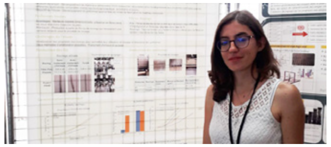
250 reached people

9 presentations

Nine SSUCHY's partners have presented their latest findings during a dedicated session at the occasion of ICNF 2021.

The conference is organized by the University of Minho, through the Fibrenamics International Platform, and is focused on the latest scientific and technical advances in natural fibres and fibre-based materials. The conference brings together various universities, research and technological centers, companies and all those interested in natural fibres materials. The conference aims to represent a forum for exchanging ideas, presenting the latest developments and trends, proposing new solutions and promoting international collaborations.

1. *Industrial Production Of High Added Value Hemp Fibres For Textile And Load Bearing Composites Using The Flax Value Chain. Some Key Figures.* **Marie Grégoire** (ENIT), Nathalie Revol, Emmanuel De Luycker, Mahadev Bar, Giorgio Rondi, Debora Botturi, Vincent Placet, Pierre Ouagne
2. *Production Of Hemp Roving Using Classical Field Management Techniques And Carded Route. Another Path In Non Flax Territories* **Mahadev Bar,** Marie Gregoire, Giorgio Rondi, Debora Botturi, Pierre Ouagne (ENIT, LCN)
3. *Natural Fibre Compostes Manufacture Using Wrapped Hemp Roving With Pa11* **Manuela Ferreira,** Chaimae Laqraa, Damien Soulat, Ahmad-Rashed Labanieh (ENSAIT)
4. *Physicochemical Surface Characterization Of Hemp Fibre Reinforced Polymer Composites: Analysis Of The Effect Of Various Fibre Surface Treatments On The Interfacial Adhesion* **Carlos Fuentes,** Dharmjeet Madhav, Aart van Vuure (KUL)
5. *Tensile Creep/Recovery Behaviour Of Hemp And Flax Fibre Reinforced Greenpoxy Composites Under Severe Environmental Condition* **Benjamin Sala,** Xavier Gabrion, Frédérique Trivaudey, Violaine Guicheret-Retel, Vincent Place (UFC)
6. *Thermal Effects On The Static And Fatigue Behaviour Of Woven Hemp Fabric/Greenpoxy Composites* **Thomas Jeannin,** Xavier Gabrion, Benjamin Sala, Taiqu Liu, Vincent Place (UFC)
7. *Damping Behaviour Of Hemp And Flax Fibre Reinforced Greenpoxy Composites* **Taiqu Liu,** Pauline Butaud, Yves Gaillard, Vincent Placet, Morvan Ouisse (UFC)
8. *Incorporation Of A Thin Polyurethane Interlayer To Improve The Hygroscopic And Mechanical Durability Of Flax And Hemp Fibre Composites* **Gilles Koolen,** Laura Bruynseels, Thomas Cambré, Aart Willem van Vuure (KUL)
9. *Effect Of Different Ageing Tests On Flexural Properties Of Non-Dry Flax Fibre/Epoxy Composites* **Maria Morissa Lu,** Aart Van Vuure (KUL)



THE 21ST NATIONAL DAYS ON COMPOSITES, BORDEAUX, FRANCE

Key figures:

1-3 July 2019

250 reached people

2 oral communications

1 poster

SSUCHY project was presented at the 21st National Days on Composites in Bordeaux, from July 1st to 3rd, 2019, with two oral presentations by Camille François and Benjamin Sala of the FEMTO-ST Institute as well as a poster directed by Anne-Clémence Corbin, PhD student at ENSAIT-GEMTEX.

The National Days on Composites is a bi-annual scientific congress organized since 1978 by the French Association for Composite Materials (AMAC). The event periodically allows to take stock of the latest scientific and technological advances, in addition it constitutes a place of meeting and privileged debates for teachers, researchers and industrialists concerned by the composites.

1. *Creep behaviour of Plant Fibre Composites* **Benjamin Sala,** X. Gabrion, V. Guicheret-Retel, F. Trivaudey, V. Placet (UFC)
2. *Development and characterization of a bio-based matrix for high-grade bio-composite applications,* **Camille François,** S. Pourchet, G. Boni, R. Sonnier, X. Gabrion, Y. Gaillard, V. Placet, and L. Plasseraud (UFC)
3. *Improvement in the weavability of preforms for composite applications with hemp/PA12 wrap rovings,* **Anne-Clémence Corbin,** D. Soulat, M. Ferreira, A. R. Labanieh (ENSAIT)

ECOMAT 2018 CONFERENCE, NANTES, FRANCE

Key figures:

12 October 2018

80 reached people

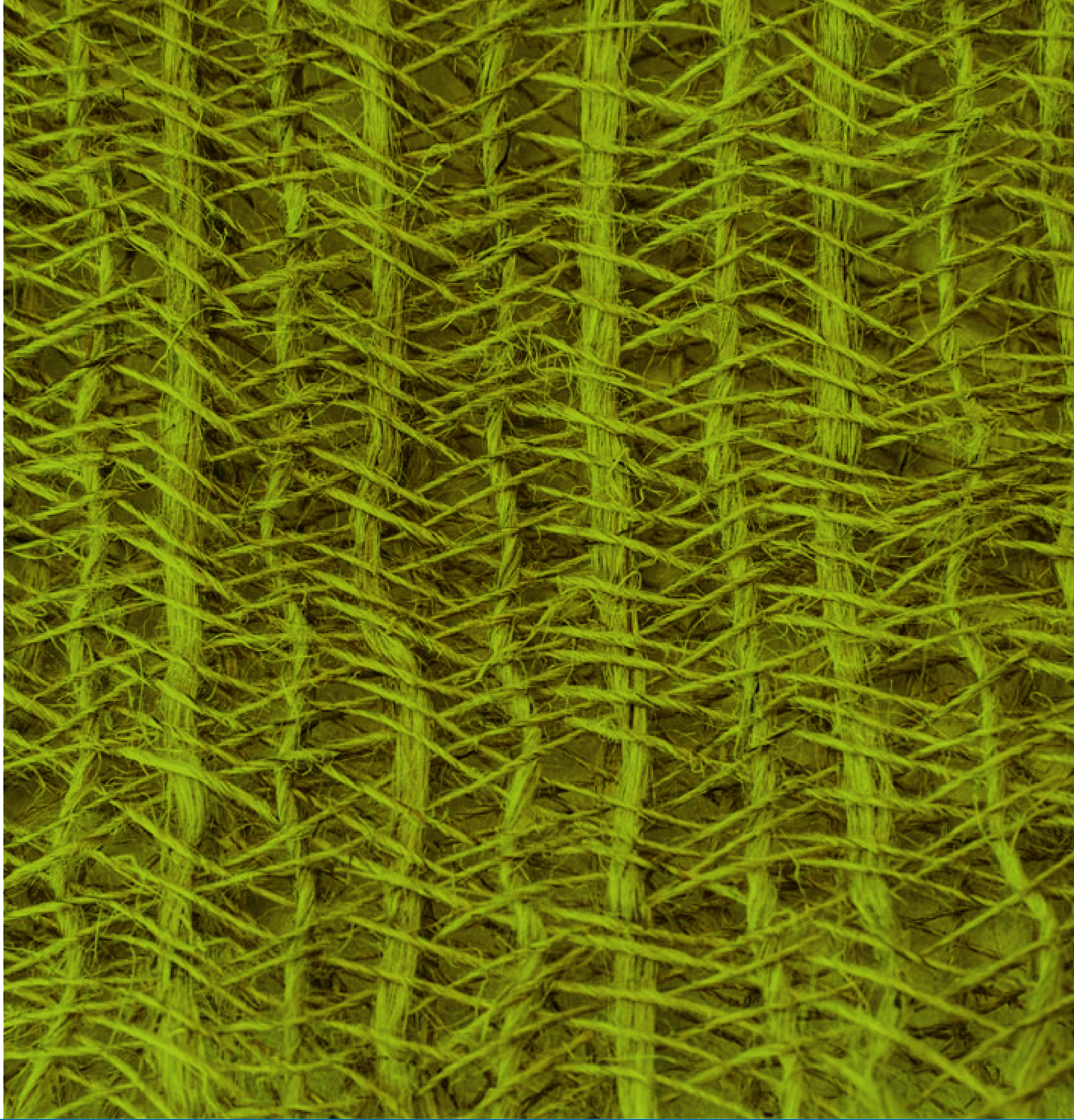
2 oral presentations and

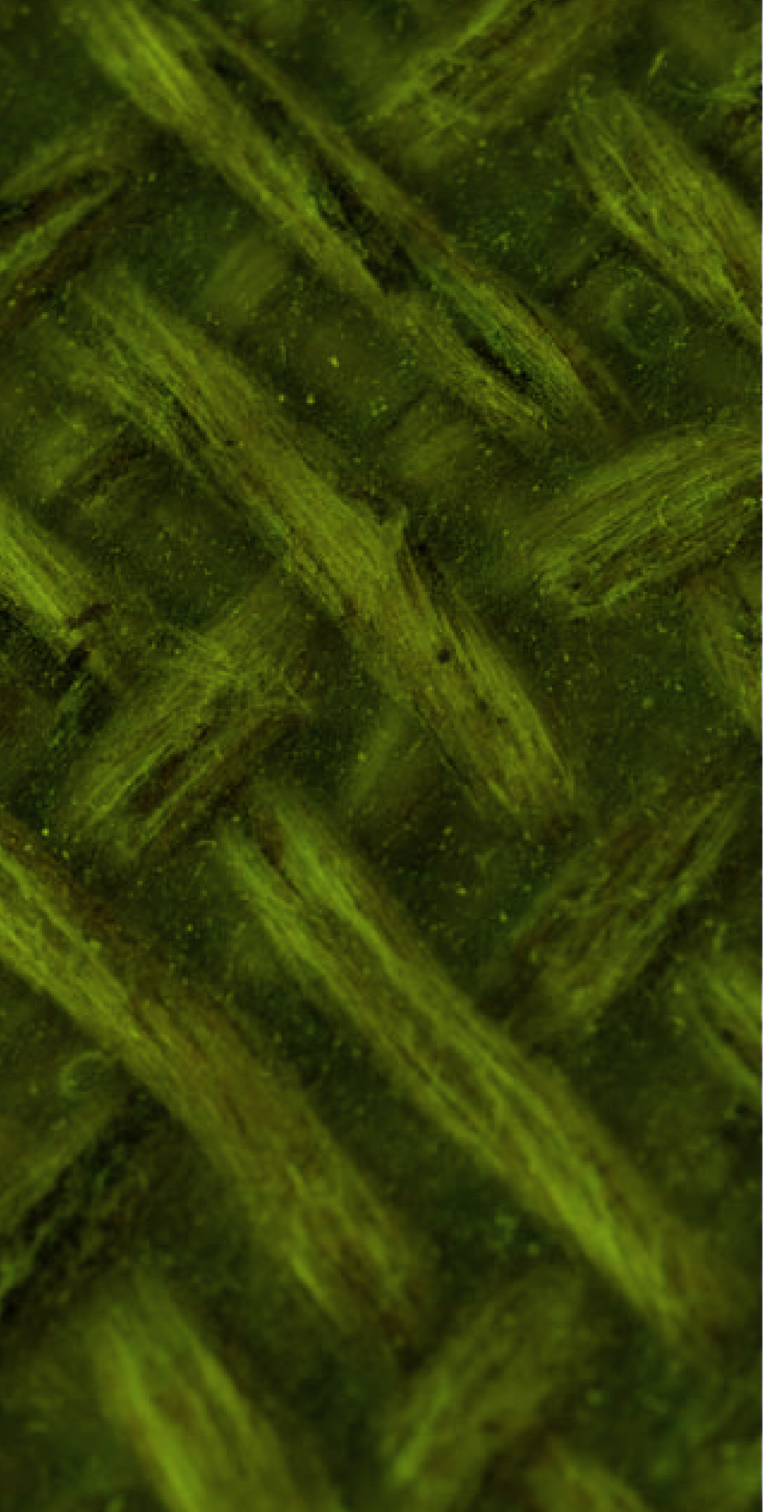
1 as an Invited Speaker

UFC and ENSAIT joint work on SSUCHY Project has been presented during the Ecomat 2018 Conference in Nantes on October 12, 2018.

UFC and ENSAIT's presentation focused on the mechanical properties of natural fibres.

Ecomat conference has for objective to bring together all current academic knowledge and feedback from industry on the sustainability of ecomaterials in the following areas: building, transport, boating, energy, sports, etc. Thus, the focus was on describing the phenomena related to the degradation of these materials on each stage of the life cycle.





ESBBC: FIRST EUROPEAN SUMMER SCHOOL ON BIO-BASED COMPOSITES

1ST ESBBC
EUROPEAN SUMMER SCHOOL ON BIO-BASED COMPOSITES
FROM PLANT & WOOD FIBRES TO ADVANCED COMPOSITES

The SSUCHY project collaborated together with 3 other European projects FLOWER, NETFIB and FibreNet for the creation, organization and sponsorship of the first "European Summer School on Bio-Based Composites – From plant and wood fibres to advance composites" - ESBBC, a 3-day event that was hosted virtually, between July 6 and 8, 2021, and initiated by the FEMTO-ST Institute of the University of Franche-Comté (coordinator of SSUCHY project). *These EU projects are the result of different research and development programmes funded by the European Union such as H2020, Interreg and Era-NET.*

This first edition has been a great success with:

160 participants more than 50% being PhD students, 26,5% Master Students and 10% were early-career researchers.

from **27** different countries,

3 days of conferences: **8** sessions ;

18 presentations and keynotes ; **31** Flash presentations

Many partners of SSUCHY project were involved in the organisation of the event and had the opportunity to present their work during several sessions.

This event brought together researchers, Masters and PhD students working in the field of biocomposites and their development, covering a wide range of disciplines, allowing them to present and discuss their technical-scientific experiences. The following 3 main topics were addressed divided into 8 sessions: (i) Testing; (ii) Manufacturing, design and durability; and (iii) End-of-life management, sustainability assessment, circular bioeconomy.

Best Flash-Presentation Award Winners

A contest was organized that awarded three prizes for the "Best PhD Student Flash Presentation" among the 31 presentations, chosen by the scientific committee.

Three prices were awarded with 4 ex-aequo presentations for the 3rd price:

1. Jason GOVILAS - University Franche-Comté, France

Investigation of the mechanics of interface between individual plant fibres using micro-mechatronics

2. Emmanuelle RICHELY - INRAE Nantes, France

Combined experimental and numerical approaches to grasp the mechanical behaviour of flax fibres and bundles

3. -Ana Carolina CONSTANCIO TRINDADE - PUC-Rio, Brazil

Natural fibre-reinforced geopolymers exposed to accelerated aging tests

- Delphin PANTALONI - University of South Brittany, France

Are biodegradable polymers suitable as matrix for biodegradable flax composites ?

- Farzin JAVANSHOUR - Tampere University, Finland

Interfacial Toughening of Flax Fibre Reinforced Composites for Better Impact Resistance

- Alexandros PRAPAVESIS - KU Leuven, Belgium

Full-field 3D Strain Mapping of Flax Fibre Composites by Means of 4D X-CT Digital Volume Correlation

SSUCHY PROJECT – FINAL EVENT

To communicate and promote the results obtained over the 5 years of SSUCHY project, a dedicated event was organised on February 9th, 2022. This online event brought 135 participants in total. Through the 15 presentations, the SSUCHY partners have brought up the achievements on the new bio-based polymers, hemp value chain and the implementation of advanced functionalities in bio-based composites, incorporated in the 4 industrial demonstrators.

The record is available on SSUCHY Youtube Channel and Presentations available on SSUCHY Website

CET+1 SSUCHY FINAL EVENT PROGRAMME

FEBRUARY 9

10:30 – 10:40 General introduction and overview of the SSUCHY project
Dr. Vincent PLACET, University of Franche-Comté

10:40 – 11:00 Elaboration of new bio-based polymers from undervalued wood and plant feedstock

- From biomass to building blocks: Green chemistry generation of lignin-derived tailored building blocks for polymers - Pr. Joseph SAMEC, Stockholm University
- From building blocks to bio-based thermoplastic and thermoset polymers - Pr. Christophe THOMAS, Chimie ParisTech

11:00 – 11:30 Innovative hemp value chain for composite reinforcements

- Highlights of scientific outcomes - Pr. Pierre OUAGNE, ENIT
- Industrial achievements and perspectives - Ing. Pierluigi FUSCO GIRARD, CEO Linificio e Canapificio Nazionale – Mazrotto Lab

11:30 – 12:05 Bio-based composites: adding value through enhanced functionalities

- Bio-based composites used and developed within the SSUCHY project, an overview - Dr. Vincent PLACET, University of Franche-Comté
- Improving the moisture durability of flax and hemp fibre composites - Pr. Aart VAN VUURE, KU Leuven
- Nouryact, a cobalt free accelerator system for unsaturated polyester curing, suitable for non-dried plant fibres - Gea SPIJKERMAN, Teamleader Crosslinking, Thermoset and Polymer Additives, Nouryon
- Damping properties of bio-based composites - Pr. Morvan OUISSE, ENSMM

12:05 – 12:45 Demonstration of the innovation through industrial applications: experience feedbacks and last barriers to remove
Pr. Fabrizio SCARPA, ACCIS, University of Bristol

- Next Generation bio-based cabinet architecture for ultimate performance, luxury, High End Loudspeaker systems - Craig MILNES, CEO Wilson Benesch
- Biobased composites in applications of biocomposites for sustainable aviation - Rosario DE LUCA, CEO of EADCO GmbH and SCYLAX GmbH
- A biobased electric scooter body; stronger, lighter, cheaper and more sustainable - Mark LEPELAAR, Co-founder and Director – Product Engineering, NPSP BV
- Potential of continuous hemp fibers for the weight reduction and CO2 emissions neutrality of automotive semi-structural parts - Arnaud Duval, Acoustic, Innovation & CAE Director, TREVES Products, Services & Innovation

12:45 – 12:55 Environmental sustainability of biobased composites
Pr. Karel VAN ACKER, KU Leuven

12:55 – 13:00 Closure Talk
Ana RUIZ, Project Officer at CBE

Online event
Registration free but limited and mandatory
For any further information: contact@ssuchy.eu

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9 GLOSSARY OF TERMS

Ageing: Deterioration/damaging of materials in pursuit of time, particularly due to effects of hygroscopic swelling and shrinkage, temperature and photo-oxidation (UV radiation).

Beating: Process that consists in beating the broken stems so as to remove the broken pieces of the woody core (shives) from the fibre bundles.

Bio-based: Composed or derived in whole or in part of biological products issued from the biomass (including plant, animal, and marine or forestry materials). materials). (Vert et al 2012).

Bio-based material: A bio-based material is a material intentionally made from substances derived from living (or once-living) organisms. These materials are sometimes referred to as biomaterials, but this word also has another meaning. Strictly the definition could include many common materials such as wood and leather, but it typically refers to modern materials that have undergone more extensive processing. Unprocessed materials may be called biotic material. Bio-based materials or biomaterials fall under the broader category of bioproducts or bio-based products which includes materials, chemicals and energy derived from renewable biological resources. Bio-based materials are often biodegradable, but this is not always the case. (https://en.wikipedia.org).

Biodegradability: refers to the breaking down of a product via microbial activity (e.g., by aerobic catabolic pathways, producing CO2, water, and biomass as end products, or anaerobically, producing CO2 and CH4), a product's "end-of life." *[Douglas G. Hayes, J Am Oil Chem Soc (2017) 94:1329–1331]*

Biomass: describes the mass of all biological organisms, dead or alive, excluding biological mass that has been transformed by geological processes into substances such as coal or petroleum. [ScienceDaily]. Biomass is plant or animal material used for energy production, heat production, or in various industrial processes as raw material for a range of products. It can be purposely grown energy crops (e.g. miscanthus, switchgrass), wood or forest residues, waste from food crops (wheat straw, bagasse), horticulture (yard waste), food processing (corn cobs), animal farming (manure, rich in nitrogen and phosphorus), or human waste from sewage plants. *https://en.wikipedia.org*

Biomass feedstock: Biomass feedstock is a viable alternative to finite fossil fuel resources to provide many of the same benefits for energy and material applications (Wei et al., 2012). Biomass feedstocks include plants, algae, forest products wastes, agricultural residues, organic fractions of municipal solid wastes, paper, cardboard, plastic, food waste, green waste, and other waste.

Biomass fractionation: The fractionation is a separation process in which a certain quantity of a mixture is divided during a phase transition into a number of smaller quantities (fractions) (https://en.wikipedia.org). The fractionation of plant materials refers to their conversion into their constituent components such as individual building blocks.

Biorefinery: A refinery that converts biomass into a spectrum of bio-based products (food, feed, chemical, materials) and bioenergy (biofuels, power and/or heat). *International Energy Agency - Bioenergy Task 42. "Bio-based Chemicals: Value Added Products from Biorefineries | Bioenergy"*

BPA: acronym of Bisphenol A which is a precursor of polycarbonates and most of polyepoxides, and is used in products ranging from food and beverage containers to thermal-paper receipts. It has been found to leach from these products to varying degrees, imparting chronic, low-level exposures via dermal, respiratory, and oral routes. [Environmental Health Perspectives, Vol.122, No. 8, A 223, 2014]

Braiding: Braiding process is a textile manufacturing technique, nowadays often used for reinforcement in composites which competes well with filament winding, pultrusion, and tape lay-up but also the weaving process, which is able to produce non-orthogonal reinforcement. In the braiding process a braiding loom deposits continuous, intertwined fibre tows to create braid architecture. At a minimal level, a braid (denoted biaxial braid) is constituted of two groups of yarns intertwined. The braiding angle is the angle between the longitudinal direction of the braided preform and the deposited fibres. This braiding angle is a key parameter in kinematic analysis of the process and also for the mechanical behaviour of the braided composite. Axial yarns could be added along the mandrel axis and in this case the braid is called a tri-axial braid. *[B. Duchamp et al.. Tensile behaviour of biaxial and triaxial braided fabrics. Journal of Industrial textiles, 47:8:2184-2204, 2018].*

Breaking: This action has as goal to break the woody core of plant stems. It is performed in the scutching lines under the action of corrugated rollers.

By-product: substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste but as being a by-product only if (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts (Directive 2008/98/EC on waste; art 5 §1).

Catalytic fractionation or Lignin-First approach: Process which consists in separating the polymeric sugar and lignin fractions in the presence of a catalyst that promotes cleavage of the lignin into aromatic monomers. *[J Am Chem Soc . 2021 Sep 22;143(37):15462-15470. doi: 10.1021/jacs.1c08635. Epub 2021 Sep 9.]*

Catalyst: In general, substance that increases the rate of a reaction without modifying the overall standard Gibbs energy change in the reaction. *[Pure Appl. Chem., Vol. 84, No. 2, pp. 377–410, 2012].*

Carding is a mechanical process that disentangles, cleans and intermixes fibres to produce a continuous web or sliver suitable for subsequent processing.

Composite: a material which is produced from two or more constituent materials These constituent materials have notably dissimilar chemical or physical properties and are merged to create a material with properties unlike the individual elements Within the finished structure, the individual elements remain separate and distinct, distinguishing composites from mixtures and solid solutions. [BIOSWITCH Glossary of terms]

Creep: Increase in material deformation over time, due to a sustained stress; irreversible creep amounts to development of damage (cracks).

Crimp: When warp and weft yarns interlace in fabric they follow a wavy path. According to pierce "crimp", geometrically considered is the percentage excess of length of the yarn axis over the cloth length. Crimp percentage is defined as the mean difference between the straightened thread length and the distance between the ends of the thread while in cloth which is expressed as a percentage. *[https://textilecollege.wordpress.com]*

Curing or reticulation: Chemical process of converting a prepolymer or a polymer into a polymer of higher molar mass and then into a network. Curing is achieved by the induction of chemical reactions which might or might not require mixing with a chemical curing agent. Physical aging, crystallization, physical crosslinking and post-polymerization reactions are sometimes referred to as 'curing'. Use of the term 'curing' to describe such processes is deprecated. *[IUPAC Gold book]*

Damping ratio: dimensionless measure describing how oscillations in a system decay after a disturbance *(Wikipedia).*

DGEBA or BADGE: Acronym of bisphenol A diglycidyl ether which is the most important chemical in epoxy resin technology prepared from epichlorohydrin and bisphenol A. *[Encyclopedia of Polymer Science and Technology, 2013]*

Durability: The ability of a product, component or material to remain functional and relevant when used as intended *(EMF, 2021).*

End-of-life product: Product at the end of its useful life that will potentially undergo reuse, recycling, or recovery *(EC-JRC, 2010, p.22)*

Environmentally-friendly: refers to the absence of environmental harm, and should be referred to either the process for making the product, the product itself, or the entire life cycle of the product. *[Douglas G. Hayes, J Am Oil Chem Soc (2017) 94:1329–1331]*

Fatigue: Mechanical ageing, deterioration of material, development of damage over time, due to sustained cyclical loading

Fibre bundles, or technical fibres: Group of fibres held together by pectic cements coming from the phloem of plant fibre stems

Glass transition temperature (Tg): The glass transition temperature is the temperature range where amorphous polymer substrate changes from a rigid glassy material to a soft, rubbery (not melted) material, and is usually measured in terms of the stiffness, or modulus, or a peak in the damping factor. The degree to which a thermoplastic material softens, its stiffness, is dependent on the crystallinity. The melt temperature is the temperature at which polymer crystals melt and the polymer flows and is generally much higher than the glass transition temperature. Crosslinked polymers and thermoplastics that contain very long polymer chains with strong intermolecular attractions do not melt and flow but remain soft until they decompose. *[Talanta, Vol 56, pp. 267–287, 2002]*

Hardener or Curing agent: For thermosets, co-reactive added to the prepolymer, and leading to the cross-linking. It plays an important role in the curing kinetics, gel time, degree of curing, viscosity, curing cycle and the final properties of the cured products.

Hackling or combing: Process that consists in separating the long strand fibres from the tows. The fibres are combed by the successive action of thinner and thinner combs.

Harvesting is the process of gathering a ripe crop from the fields.

Hybrid Yarn: Yarn mixing two natures of material. Thermoplastic hybrid yarns contain thermoplastic fibers and fibrous reinforcement material. Hybrid yarns can be manufactured by various means, including co-wrapping, core spinning and commingling, aiming to give uniform distribution of matrix and reinforcement fibers as well as to reduce the damage to reinforcing fibers. *[adapted from : R Alagirusamy et al. Hybrid Yarns and Textile Preforming for Thermoplastic Composites, Textile Progress, 38:4, 1-71, 2006]*

Infusion: Resin Infusion is a process by which vacuum draws resin into a dry fiber laminate in a one sided mold. A rigid or flexible film membrane is placed over the top and sealed around the mold periphery. Resin infusion is considered a "Closed Mold Process". There are many names and acronyms for the resin infusion process or very similar processes. The vacuum-assisted resin infusion (VARI) technology is one of the well-established processes used to fabricate performant composites

Interface: Interface is the two dimensional boundary between two surfaces.

Linear density: Defined in textiles as the linear mass density which is the amount of mass per unit length (titer in textile engineering). This property is also associated to the fineness. Linear density is expressed in tex, defined as the mass in grams per 1 000 meters. *[adapted from Wikipedia]*

Life cycle: the consecutive and interlinked stages of a product system, from raw material extraction or generation from natural resources to final disposal *(ISO 14040:2006, p.2).*

Life cycle assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle *(ISO 14040:2006, p.2).*

Life cycle impact assessment (LCIA): phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product *(ISO 14040:2006, p.2).*

Loss factor: ratio of the energy dissipated per cycle to maximum stored strain energy in the cycle *(Own definition).*

Macromolecule or polymer molecule: Molecule of high relative molar mass (in the range of 2000 – 1 000 000 g/mol), the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molar mass (the monomers). *[Pure Appl. Chem., Vol. 84, No. 2, pp. 377–410, 2012]*

Monomer: A molecule (molar mass of 50 – 200 g/mol) which can undergo polymerization, thereby contributing constitutional units to the essential structure of a macromolecule. *[IUPAC definition]* Monomers refer to the compounds that we synthesize, mostly consisting of diepoxides.

Natural fibres: Any hairlike raw material directly obtainable from an animal, plant, or mineral source and convertible into nonwoven fabrics such as felt or paper or, after spinning into yarns, into woven cloth *(based on Encyclopædia Britannica, 2021).*

Plant Stem: A stem is the main structural support for most complex plants. The stem is essentially the skeleton of a plant that supports the leaves in which photosynthesis takes place. A complex plant is comprised of three main components: the roots, the stem, and the leaves.

Polymerization (EU) or polymerization (GB): Process for converting a monomer, or a mixture of monomers, into macromolecules. *[Translated from: Vocabulaire de la chimie et des matériaux, 2018]*

Prepolymer: Molecule, oligomer or polymer capable of undergoing subsequent polymerization through reactive groups. *[Translated from: Vocabulaire de la chimie et des matériaux, 2018]*

Prepreg: A fibrous material pre-impregnated with a particular synthetic resin.

Raw material: primary (virgin) material or secondary material (which includes recycled material) that is used to produce a product *(ISO 14040:2006, p.3).*

Recycled: having been used before and then put through a process so that it can form a new product *(https://dictionary.cambridge.org/).*

Renewable resource: A renewable resource is a natural resource which will replenish to replace the portion depleted by usage and consumption, either through natural reproduction or other recurring processes in a finite amount of time in a human time scale. Renewable resources are a part of Earth's natural environment and the largest components of its ecosphere. A positive life cycle assessment is a key indicator of a resource's sustainability. *["Management for a Small Planet" by Jean Garner Stead and W. Edward Stead, M.E. Sharpe 2009]*

Retting is a process employing the action of micro-organisms and moisture on plants to dissolve or rot away much of the cellular tissues and pectins surrounding bast fibre bundles, and so facilitating separation of the fibre from the stem. It is used in the production of fibre from plant materials such as flax, hemp, jute stems and coir from coconut husks. Retting can be performed in water (water retting) by plunging the whole stems in ponds or flowing water, or by laying down the stems on the ground (dew retting). Because of water pollution hazard, classical water retting is forbidden in Europe. *[Wikipedia]*

Roving: When sliver is drawn further and given a slight twist, it becomes a roving.

RTM: Resin transfer moulding (RTM) is the designation for a technology where, in general, a fibre preform is placed in a female mould, the male mould closes leaving a gap to allow the resin to be injected and to impregnate the fibres. *[Fibrous and Composite Materials for Civil Engineering Applications, 2011]*

Scutching is the process that consists in separating the fibres from the rest of the plant stem materials. It is used for flax and hemp mainly. The scutching process can be separated in two sub-processes: Breaking, beating.

Sensitivity analysis: systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study *(ISO 14040:2006, p.5).*

Stiffness: extent to which an object resists deformation in response to an applied force, in the elastic regime *(Wikipedia)*

Strength: In mechanics of materials, the strength of a material is its ability to withstand an applied load without failure; the ultimate strength is then the stress at failure.

Sustainable: causing little or no damage to the environment and therefore able to continue for a long time / using methods that do not harm the environment so that natural resources are still available in the future *(https://dictionary.cambridge.org/).*

Sustainable materials: Sustainable materials are materials used throughout our consumer and industrial economy that can be produced in required volumes without depleting non-renewable resources and without disrupting the established steady-state equilibrium of the environment and key natural resource systems. Such materials vary enormously and may range from bio-based polymers derived from polysaccharides, or highly recyclable materials such as glass that can be reprocessed an indefinite number of times without requiring additional mineral resources. http://sustain.rutgers.edu/

Synthon or building-block: Molecular entity used in the synthesis of a molecule in order to introduce a given structural unit. *[Translated from: Vocabulaire de la chimie et des matériaux, 2018]*

Tenacity: Defined as the tensile strength related to the linear density (expressed in N/tex) *[adapted from Wikipedia]*

Thermoplastics: Material made of polymeric chains (arranged in linear or branched manner, not cross-linked) linked by intermolecular interactions (weak) like Van Der Waals forces and hydrogen bonds. Thermoplastics can be re-melted and reshaped a number of times. They move from the rigid state to the malleable state by a rise of temperature.

Thermosets: polymers in which a cross-linking reaction occurs promoting chemical bonding between macromolecular chains and creating a three-dimensional (3D) network (insoluble and infusible). Thermosets are irreversibly solid after polymerization, so they cannot be molten anymore. *[Fibrous and Composite Materials for Civil Engineering Applications, 2011]*

Tow is a generic name that groups coarse or broken fibre, removed during processing of flax, hemp or jute during scutching (scutching tows) or hackling (hackling tows). Tows are generally cut into stapled fibres.

Twist Level: The spinning process gives the yarn a twisted structure, where twist is the primary binding mechanism. Twist induces inter-fibre friction and thus imparts processability to the yarn. The addition of twist in yarns affects the stress transfer between fibres within the yarn and thus influences both (i) the tenacity of the yarn and the (ii) fracture mechanism of the yarn. In the textile industry, twist is defined by (i) twist direction (S or Z), (ii) twist level, T (tpm: turns per meter) and (iii) twist multiplier:

In composites, fibre twist generally lowers the mechanical properties (modulus and strength).

[D.U. Shah et al. Modelling the effect of yarn twist on the tensile strength of unidirectional plant fibre yarn composites, Journal of Composite Materials, 47(4) 425–436, 2013]

Thermo-compression / Hot pressing: Forming technique involving the simultaneous application of external pressure and temperature.

Transmission loss: Transmission loss (TL) is defined as the difference between the power incident on a sample and that transmitted downstream into an anechoic termination *(Wikipedia)*

Unidirectional: refers to a composite reinforcement made of purely aligned fibres.

Waste: any substance or object which the holder discards or intends or is required to discard *(Directive 2008/98/EC on waste; art 3 §1).*

A Warp satin is warp-faced, while a **weft satin** is weft-faced. These weaves are often used together to create patterns in the fabric. In warp- and weft-faced satins the intersections of warp with weft are distributed so that they are never adjacent. The smallest number of ends and picks on which it is possible to construct a regular satin is 5. In a satin fabric the number of interlacing points is low, leading to a substantial section of non-crimped (interlaced, thus curved) fibre. Satin fabrics also have a very good drapability due to the limited interlacing. *[Adapted from Woven textiles: principles, developments and applications Ed. K.L. Gandhi, Publisher Woodhead Publishing, 2012].*

Weaving: In traditional weaving, there are two sets of yarns, perpendicular to each other, interlaced to form a woven fabric. While one set of the yarns that runs lengthwise along the weaving machine direction is called warp, the other set of the yarns that runs transversely from one side to the other side of the machine is called weft *[Woven Fabrics, Ed. H.Y. Jeon, Publisher Intechopen, 2012].*

Weave pattern: The interlacing pattern of the warp and weft is known as the weave. A woven fabric is made up of many elements including the weave and the component yarns and fibres. All these elements, as well as any treatments or finishes applied, will affect the final fabric in terms of its appearance, handle, drape and behavior in use. Plain weave is the simplest and most frequently used weave of all. Because it has the maximum number of interlacing or binding points possible, it is stronger as a textile than a fabric which is otherwise identical but made in another weave.

Yarn is a long continuous length of interlocked fibres suitable for use in the production of textiles. The interlocking effect can be obtained using several methods to obtain different types of yarns

Roving type yarn is a roving which fibres are bound together using an adhesive

Young's (or elastic) modulus: mechanical property that measures the stiffness of a solid material. It defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material in the linear elasticity regime of a uniaxial deformation *(Wikipedia)*

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