SUSPENS

Design sustainable composites

Lightweight and sustainable composite parts for the transportation sector.

2026

BOOK OF RESULTS.

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1 ABOUT SUSPENS.

1.1 Foreword

Composite materials are widely used in the transportation sector today because they are strong yet very light materials that provide engineers with opportunities to reduce both fuel-consumption and CO_2 emissions of the vehicles.

The manufacturing of such composite structures is however known to have a significant impact on the environment. First, the raw materials are often derived from petrol-based resources, their production requires a lot of energy and finally, they are inherently difficult to recycle.
The SUSPENS project has aimed to significantly reduce this impact by developing bio-based and recycled raw materials but also low-energy processes to produce and recycle these composite structures at the product end-of-life.

The bio-based materials developed in the project have the potential to compete with pertrol-based products on the market and could be produced tomorrow from by-products of Europe's agricultural and forestry sectors. In parallel, advanced recycling technologies will make it possible to recover high-performance reinforcement fibres from industrial waste and end-of-life wind turbine blades, transforming these waste streams into valuable materials.

By combining knowledge, expertise and resources around this common objective, Horizon Europe acts as a powerful accelerator for the development and industrial deployment of new technologies. Collaborative projects such as SUSPENS and its sister projects in the Eco-composites cluster are bringing together experts, engineers, researchers and industrial partners from across Europe, creating a unique environment for innovation.

So today, we're excited to share with you the progress we have made, the solutions we have developed, and how we believe they can make a real difference—not just for the transportation sector, but for the environment and for all of us.

Mehdi Marin,
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1.2 Main impacts & key figures

START 01 01 23

42 MONTHS

FINISH 30 06 26

100 % EU FUNDING

4 995 848 € TOTAL PROJECT BUDGET

12 PARTNERS

SUSPENS AMBITIONS

To develop sustainable and safer composite structures to **reduce the CO_2 footprint** of the transportation sector.

SUSPENS RESEARCH CHALLENGES

1. High performance thermoset resins > **develop up to 95% bio-sourced fast curing epoxy and polyesters resins**
2. **Increase mechanical properties of bio-sourced and recycled reinforcement fibres** (cellulose, lignin-based carbon fibre, recycled carbon fibre and recycled glass fibre)
3. Optimise the manufacturing and recycling processes to **reduce CO_2 emissions of at least 20%**
4. **Demonstrate lightweight, high performance and fully renewable composites and structures** through 3 demo-cases / 3 manufacturing applications :

Aerospace
> Aircraft winglet

Automotive
> Battery pack

Leisure boat
> Deck and hull

SUSPENS APPROACH

Lightweight structures

Composite sandwich & hollow parts
giving
Highest stiffness to weight ratio
leading to
Reduced energy consumption in the transportation sector
demonstrated on
3 applications / industries

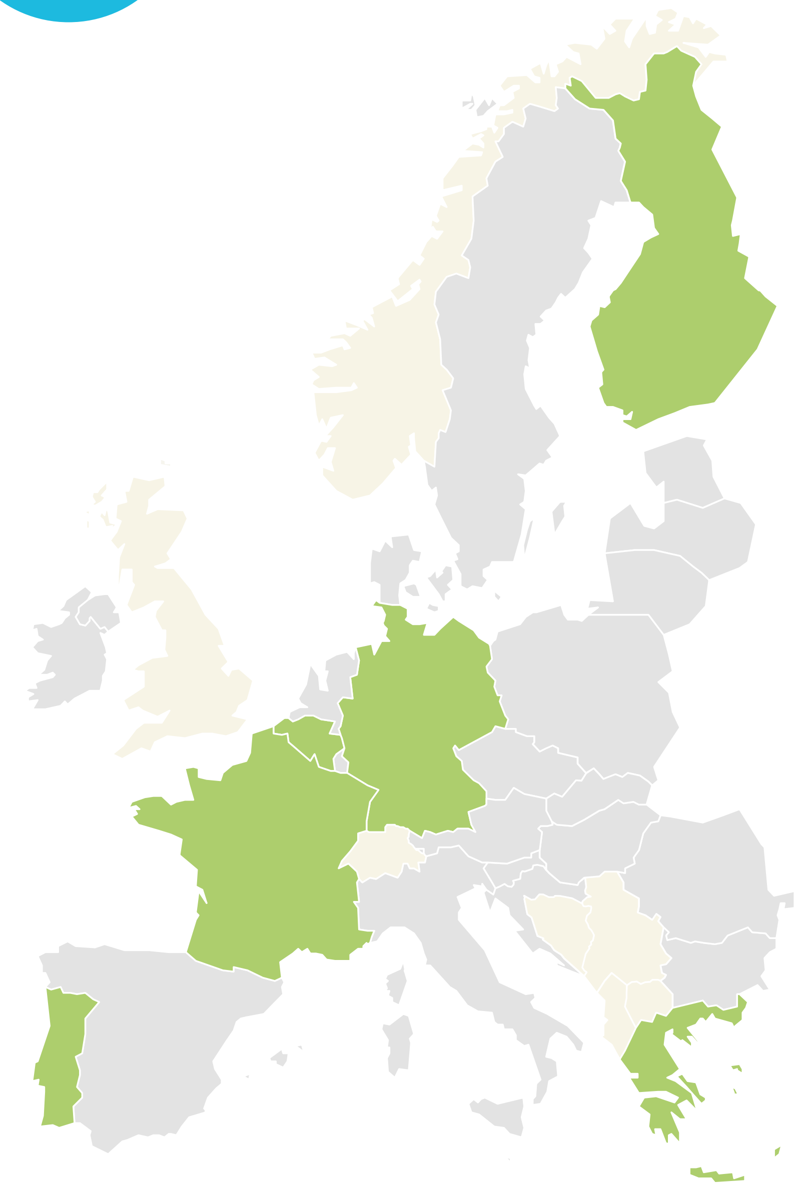
Environmental impact reduction & sustainability

- **Ingredients**
- **Manufacturing process**
- **End-of-Life**

Cost efficiency

- Ingredients: Bio-based, Recycled, Fast-cure
- Manufacturing process: Energy-efficient, Multi-functionnal
- End-of-Life: Separable, Reprocessable

1.3 SUSPENS consortium



IRT Jules Verne is a private, non-profit and collaborative French industrial R&D centre dedicated to manufacturing and robotics. Powered by a robust network of over 100 French partners, the institute's roadmap and activities are driven by industrial and market needs to serve four strategic industrial sectors: aeronautics, shipbuilding, the automotive industry, and renewable energy. Its primary mission is to boost the competitiveness of industry by developing disruptive technologies for advanced manufacturing processes. Fully integrated into the European research ecosystem, IRT Jules Verne maintains a strong presence in EU roadmaps and projects, with a proven track record of over 25 EU-funded projects.

www.irt-jules-verne.fr

Experts in composites technologies for over 40 years, Compositec designs and manufactures technical and painted parts made from thermoset and thermoplastic composite materials. Based in France, with its R&D center in Saint-Malo and its two production plants in Saint-Méloir and Theilay, the company delivers lightweight and high-performance solutions for multiple industries.

www.compositec.eu

EMC2 cluster, created in 2005 , is the European manufacturing technology cluster. EMC2 gathers a network of 400 members, composed of large enterprises, research & technical organisations and more than 200 SMEs. EMC2 aims to foster the emergence of collaborative projects and to reinforce the innovation territoral ecosystem by structuring 5 sectors (equipment goods, energy, aeronautics, shipbuilding and ground transportation) in a common and transversal approach : the advanced manufacturing.

www.pole-emc2.fr

The Institute of Chemistry (ICN) is a joint research laboratory between CNRS and UCA, composed of four main research groups. The Eco-compatible polymer group (MAPEC) within ICN has developed an internationally-recognized expertise on biomass derived materials and valorization of monomers/polymers from biomass into new commodity materials; kinetics of polymerization/phase transitions, thermo-mechanical characterization, polymerization mechanisms.

https://icn.univ-cotedazur.fr

Aalto-yliopisto

The AALTO research team is located at the department of Bioproducts and Biosystems at Aalto University, Finland.
The Biopolymer Chemistry and Engineering group focuses on the development of new routes to gain high value-added products from renewable polymers.
The group has estensive experience in the production of multi-component fibres and filaments comprising carbohydrates, lignin, chitosan, keratin and other biopolymers.
www.aalto.fi/en

Centexbel is the scientific and technical centre for the textile and plastic processing industry. It has strong links to the Belgian industry for which it performs testing, consultancy, and research.
Centexbel is active in several research domains including functional thermoplastic textiles, fibre-reinforced plastics, textile functionalisation and surface modification.
www.centexbel.be/en

IRES is an independent Belgian consulting company. IRES has a core business and wide experience in the fields of Life Cycle Assessment & Life Cycle Costing, Exposure and Risk Assessment, Standardization, Data Management Plan, Machine learning, Quality assurance and Data analysis. IRES provided customized and tailored solutions on demand.
www.innovation-res.eu

Orineo is a Belgian technology SME dedicated to the transition towards a biobased economy. Central in Orineo's philosophy is the concept of Cradle-to-Cradle: our products must all be fitting in the biogenic cycle and suited for C2C gold certification.
Orineo has developed and is commercializing a 100% biobased, non-toxic and non-persistent thermosetting resin branded as OriBond and suited for agglomerating granules into panels, protective coatings and production of High Pressure Laminate.
www.orineo.com

WH Lipex is a worldwide leading supplier in glass fibre technology. LIPEX consults with its clients on an individual basis thus supplying the best possible manufacturing solutions for their respective glass fibre industries.
www.lipex.de

APM is an industrial manufacturer of composite parts and structures based in southwestern Portugal and founded in 1966. It has more than 50 years of experience in the manufacturing of a wide range of composite products, large and small.

Megara Resins is a diversified manufacturer and supplier of raw materials for industrial and architectural coatings as well as rosin-based and other synthetic resins for the paint, adhesive, paper and construction industry. For over 50 years, Megara has been a pioneer in creating innovative technologies to help coatings formulators meet their customers' most demanding applications. Today, the company remains firmly committed to the pillars of innovation and new technologies and is widely regarded as being the most innovative Greek supplier to the coatings industry through its continued investment in R&D, technical support and new product development.
www.megararesins.com

NTUA is the oldest and most prestigious educational institution in Greece. The NTUA team comprises of chemical, mechanical, metallurgical engineers, physicists, chemists and technicians, specialized in the fields of materials research and development, possessing a very experienced staff as well as extensive facilities for materials processing and characterisation.
www.r-nano.gr

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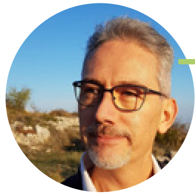

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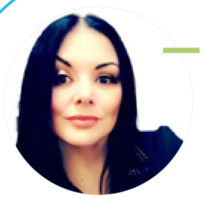
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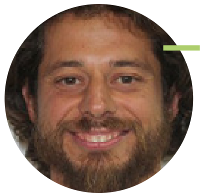
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2 RESINS.

Cross-linked epoxy and unsaturated polyester resins are key thermosetting polymers, widely used as composite matrices. Bio-based alternatives to petroleum-derived resins are gaining interest due to environmental concerns, sustainability, regulatory pressures on VOCs, and market demand for eco-friendly products. Research explores sources like plant oils and lignin to develop sustainable resins that match conventional performance while offering biodegradability. However, current bio-based content remains below 50%.

In SUSPENS, we have explored formulations with the highest bio-based content, focusing on their suitability for infusion, compression molding, and resin transfer molding. Among other characteristics, we have tested a range of monomers and hardeners and compared viscosities, curing behavior, mechanical properties, and glass transition behavior of formulated resins to guide selection for SUSPENS applications.

2.1 Bio-based UPR formulations

What if the key to greener, safer composites lies in replacing a single chemical?

Unsaturated polyester resins (UPRs) are widely used in sectors like automotive, marine, and construction. Yet most conventional UPRs still rely on styrene, a volatile, potentially hazardous diluent that raises environmental and health concerns. Megara Resins has worked on the development of the next generation of bio-based UPRs with reduced styrene content, combining sustainability with the performance required for demanding, real-world applications.

UPRs explained: the role of styrene

UPRs are usually produced through the direct reaction (polycondensation) between diols and unsaturated dibasic acids or anhydrides, resulting in a polyester that contains carbon-carbon double bond along its backbone. To render this pre-polymer processable and curable, styrene is added as a reactive diluent. It lowers the viscosity for easier handling and, during curing, copolymerizes with the unsaturated sites, resulting in a rigid, crosslinked structure that defines the final material's structure and performance[1].

Seeking safer alternatives

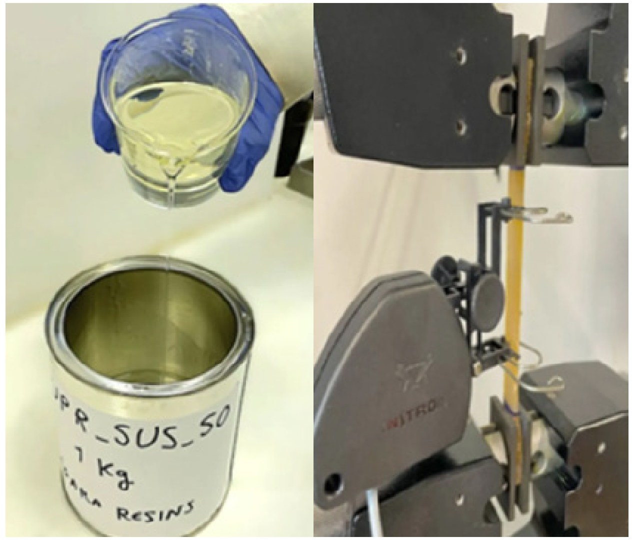
Replacing styrene is no simple task, as the choice of reactive diluent affects not only the viscosity and reactivity of the resin but also key properties of the final material, such as mechanical strength and glass transition temperature. Bio-based candidates like itaconic acid derivatives and methacrylated natural compounds are being explored as safer, more sustainable alternatives that balance processability with performance[2].

Our approach

In the framework of the SUSPENS project, Megara Resins investigated several bio-based or less toxic alternatives to styrene. Particular focus was given to isobornyl methacrylate (IBOMA), dimethyl itaconate (DMI), and an acrylated ester of glycidyl versatate (ACE), selected for their favourable reactivity and reduced hazard profile compared to styrene. Key properties of the resulting resins, comprising acid value, viscosity, gel time, glass transition temperature (Tg), and tensile strength were evaluated using ASTM and ISO standard methods.

50%
bio-based content
with equivalent properties than a reference UPR.

50%
styrene substitution
Styrene has been mixed with a bio-based and non-toxic alternative.



Bio-based candidates like itaconic acid derivatives and methacrylated natural compounds are being explored as safer, more sustainable alternatives that balance processability with performance.

Key findings

It was demonstrated that DMI can substitute styrene up to 50 % wt., as full replacement led to high viscosities and lower reactivity towards curing.

Notably, resins diluted in DMI/STY mixtures displayed tensile properties comparable to the benchmark ones, although DMI's high cost remains a limitation. ACE was synthesized in the lab from versatic acid glycidyl ester (CARDURA™ E10P) and evaluated as a potential alternative to styrene.
It exhibited excellent compatibility with the prepolymer; however, full substitution resulted in unacceptably high viscosities. Partial replacement up to 30 % wt. was feasible, yielding resins with acceptable processing behaviour and, in most cases, improved tensile properties.

Last, IBOMA as styrene substitute, exhibited moderate compatibility at room temperature resulting in UPRs with increased viscosity and turbidity. **However, the use of IBOMA/styrene blends resulted in resins that met processing specifications and displayed sufficient mechanical performance.**

Overall, the strategy of partial styrene substitution, particularly with ACE and IBOMA, proved effective in maintaining resin performance while reducing styrene content.

From lab to application

The next step focused on evaluating the performance of these bio-based UPR formulations in advanced applications such as Sheet Moulding Compound (SMC) technology, widely used in the automotive industry for the production of structural and semi-structural composite parts. During SMC processing, the UPR resin must initially exhibit low viscosity for efficient fibre impregnation, followed by a controlled thickening phase. This is achieved through the addition of alkaline agents (e.g. MgO), which react with the resin's terminal carboxylic groups, forming a 3D network[3]. Acid value and molecular weight are key parameters, affecting both the kinetics and quality of the thickening process[4]. According to the results, a molecular weight of 1600–1800 g/mol, with a corresponding acid value of 25–35 mg KOH/g, is required to achieve proper thickening behaviour in SMC-grade UPRs. In addition, partial substitution of styrene with IBOMA had no adverse effect on the thickening profile, maintaining the final viscosity (penetration depth) at levels suitable for SMC processing. Conversely, replacing part of the styrene with ACE resulted in slower thickening and lower final viscosity, likely due to steric hindrance from its bulky, branched structure, which may limit interactions with the thickening agent.

These findings support the potential use of IBOMA as a bio-based diluent that combines processability with reliable performance in automotive composite applications.

Conclusions

This study highlights the potential use of bio-based reactive diluents as viable alternatives to styrene in UPR resins. Among the candidates, IBOMA emerged as the most promising, combining sustainability with performance.
Future work will focus on scale-up and the development of demonstrators, paving the way for safer, greener composite materials.

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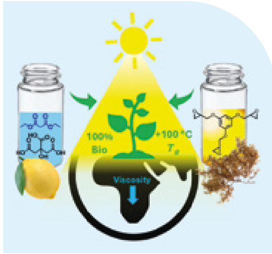
[1] Athawale, A.A. & Pandit, J.A. Unsaturated Polyester Resins: Fundamentals, Design, Fabrication, and Applications. Elsevier, 2019, Ch. 1, pp. 1–42. [2] Gandini, A. & Lacerda, T.M. "From Monomers to Polymers from Renewable Resources: Recent Advances." Prog. Polym. Sci., 2015, 48, 1–39. [3] Han, C.D. & Lem, K.W. "Rheology of Unsaturated Polyester Resins II: Thickening Behavior of Unsaturated Polyester and Vinyl Ester Resins." J. Appl. Polym. Sci., 1983, 28(2), 763–778. [4] Freitag, B. & Jäger, C. "Thickening Paste for Unsaturated Polyester Resin Mixtures and Its Use in Sheet Moulding Compounds." Eur. Patent EP0926188B1, 2001.

2.2 Bio-based epoxy resins

The green revolution in plastics: designing and dismantling the next generation of high-performance materials.



Biobased thermoset polymers for high-performance applications. (Reactive and Functional Polymers 224 (2026) 106763)

1 A fully bio-based epoxy thermoset for high-performance applications

The polymer industry is dealing with a critical challenge to develop sustainable resins providing both thermal and mechanical performances required for demanding structural applications. Traditional thermoset epoxies, while showing dimensional stability, chemical resistance, and high stiffness, are generally based on petroleum-derived monomers like bisphenol-A (BPA), a known endocrine disruptor.

Recent work demonstrates a feasible solution, a bio-based epoxy thermoset formulation that combines low-viscosity processing with high thermal stability, and fast curing capability.

PHTE-based resin with anhydride hardener

Phloroglucinol tris-epoxy resin (PHTE), derived from phlorotannins found in brown algae, serves as the rigid aromatic epoxy backbone. This trifunctional monomer provides the structural integrity required for high-performance networks. A bio-derived anhydride hardener (BH), accessible from renewable biomass sources, was used to cure PHTE. This hardener contributes to increasing rigidity, thermal stability, and chemical resistance of the resulting polymer network. The formulation PHTE_BH was prepared through simple mixing of PHTE and BH at room temperature using a stochiometric ratio: $\left(R_{\mathrm{PHTE}}\left(\frac{n\ (COOH)}{n\ (epoxy)}\right) = 0.8\right)$. This system shows the viscosity of 148 Pa. s at room temperature. However, the lowest viscosity (non-isothermally measured) was 0.1 Pa. s at 102 °C with the gelation time at 32 minutes. These values demonstrate good processability and compatibility with liquid composite manufacturing techniques. Additionally, a reaction accelerator was identified after a screening phase. The use of this accelerator has led to a significant Tg increase (175°C) and reduction in curing time. The effect of curing optimization on thermo-mechanical properties and processing time is summarized in *Table 1*.

Table 1

PROPERTY	PHTE-BH (Standard curing without accelerator)	PHTE-BH (Fast curing using 3% accelerator)	Relevance for high-performance applications
Glass transition temperature (Tg, DMA)	131 °C	175-180 °C	High temperature structural composites
Young's modulus	~2342 ± 234 MPa	~2.2-2.3 GPa	Load-bearing materials
Thermal stability ($T_{10\%}$, air)	>348 °C	>348 °C	RTM/ infusion compatible
Lowest viscosity (non-isothermally 25 to 180 °C)	0.1 Pa•s (102 °C)	-	RTM compatible
Lowest viscosity (isothermally)	1.4-2 (Pa. S) 73 °C	-	RTM compatible
Curing time	~6 hours in total (1-50 °C) (2-160 °C) (3-180 °C)	5 minutes at 160 °C	Fast industrial cycle

Scientific significance

This formulation demonstrates that fully bio-based epoxy systems (potentially ≥97 %) can achieve:

- **High glass transition temperature** (up to 180 °C)
- **Excellent thermal stability** (T10%= 348 °C)
- **Very low viscosity** enabling liquid processing
- **Fast curing compatible with industrial manufacturing**
- The combination of an **aromatic epoxy backbone** and **optimized curing conditions** results in **a highly crosslinked and thermally stable network**.

This system targets aerospace and automotive composites, marine and structural components, and high temperature coatings which represent a strong bio-based alternative to conventional petroleum-based epoxy systems.

PHTE-based resin with Eutectic hardener

Furthermore, another bio-derived hardener, a green eutectic hardener (CADEM) produced from citric acid (CA) and diethyl malonate (DEM) was used to cure PHTE as the biobased curing agent. Through preparation of the CADEM eutectic mixture $\left(R_{\mathrm{eutectic}}\left(\frac{n\ (DEM)}{n\ (CA)}\right) = 0.5,1\right)$, the solid citric acid melting temperature (~ 153 °C) decreased significantly, leading the liquid like eutectic mixture, mixes homogeneously with PHTE at room temperature.

The optimal formulation uses an acid to epoxy ratio $\left(R_{\mathrm{PHTE}}\left(\frac{n\ (COOH)}{n\ (epoxy)}\right) = 0.8\right)$, which balances reactive site availability with network formation efficiency. This results processing viscosities as low as 0.43 and 9 Pa• s non-isothermally and 1.4-2 Pa. s and 0.1-2 Pa. s (73 °C, 80 °C) isothermally for PHTE_CADEM-0.5 and PHTE_CADEM-1 respectively, under mild curing conditions comparable to industry epoxy systems.

Key performance metrics

The cured thermosets exhibit interesting properties for fully bio-based materials:

PROPERTY	PHTE-CADEM-0.5	PHTE-CADEM-1	Relevance for High-Performance Applications
Glass transition temperature (Tg, DMA)	114 °C	83 °C	Suitable for automotive/aerospace composites, coating
Young's modulus	~2.8 GPa	~2.8 GPa	Matches structural engineering requirements
Thermal stability ($T_{10\%}$, air)	>300 °C	>300 °C	Wind turbine blades, high-temp coatings
Lowest viscosity (non-isothermally)	9 Pa•s (25 to 180 °C)	0.43 Pa•s (25 to 180 °C)	RTM compatible
Lowest viscosity (isothermally)	1.4-2 (Pa. S) 73 °C	0.1-2 (Pa. S) 80 °C	-

Scientific significance

The eutectic strategy addresses three critical limitations of bio-based thermosets simultaneously:

1. Processability: Preparation of the CADEM eutectic hardener reduces CA's melting temperature significantly, enabling industrial-scale mixing.

2. Network homogeneity: Hydrogen bonding between DEM's α-carbon and CA's hydroxyl groups activates carboxylic acids for nucleophilic attack on oxirane rings, ensuring homogeneous curing.

3. Performance retention: PHTE's aromatic trifunctional structure maintains high Tg and modulus despite high renewable carbon content. The curing mechanism, oxirane ring opening and forming β-hydroxy esters is confirmed by in situ FTIR, showing complete oxirane consumption and stable ester/carbonyl formation. Furthermore, this catalyst-free chemistry operates under mild conditions (50°C initial cure, 160°C post-cure).

Implications for high-performance applications

This formulation targets markets where thermosets dominate such as aerospace composites, automotive, coating and wind turbine blades. The combination of rheological, and thermo-mechanical properties, makes this formulation a promising alternative to DGEBA for high-performance applications which proves that bio-based feedstocks can deliver engineered performance, not just environmental credentials.

2 Chemical recycling

Creating a bio-based plastic is only half the battle. The second study explored how to recycle these complex networks to recover valuable and reusable products.

The strategy of "fragile bonds"

To make a material recyclable, researchers have exploited "fragile" points into the polymer called ester linkages. These bonds act like a security seal that remains strong and stable during use but can be broken under specific chemical conditions at end-of-life.

Chemical recycling using solvolysis

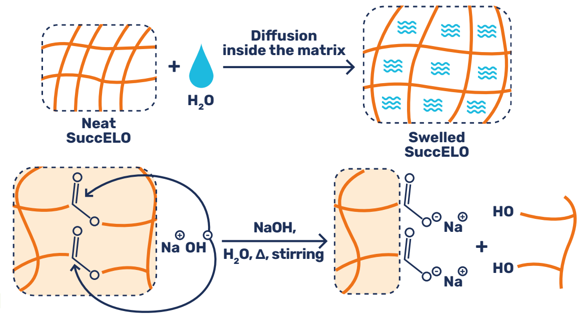
The recycling process uses solvolysis. In the case of polyesters the chemical reaction is a saponification, the same basic chemical reaction used for centuries to make soap. By placing the polymer (in this case, "SuccELO," made from linseed oil and succinic acid) in a basic solution like sodium hydroxide, the network is dismantled by attacking ester bonds, allowing the recovery of valuable polyacids that can be further reused in thermosetting resins. By using original in situ techniques combined with kinetic analyses, our group identified four critical stages in this recycling process:

1. Diffusion: The solution begins to penetrate the solid material.

2. Solvolysis: The chemical attack starts breaking the ester bonds, forming carboxylate ions.

3. Autocatalysis: The products created during the reaction help dissolve the rest of the polymer faster, accelerating the process.

4. Final diffusion: The resulting small molecular chains diffuse away into the liquid, ready to be recovered and reused.



Schematic overview of different mechanisms involved in the chemical recycling of SuccELO. (ACS Sustainable Resour. Manage. 2024, 1, 1834–1844, © 2024 American Chemical Society)

Closing the loop

These advancements prove that sustainability and high performance are no longer mutually exclusive. By using renewable resources, like algae, linseed oil, and fruit acids, and designing structures that can be chemically recycled through solvolysis, we are moving toward a world where aircraft parts or car components can be harvested from plants and reused in new thermosets at end-of-life. The carbon loop is finally being closed.

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2.3 Fire retardancy

Bio-based flame-retardant thermoset resin formulation with high glass transition temperature for advanced composites.

Context & technical challenges

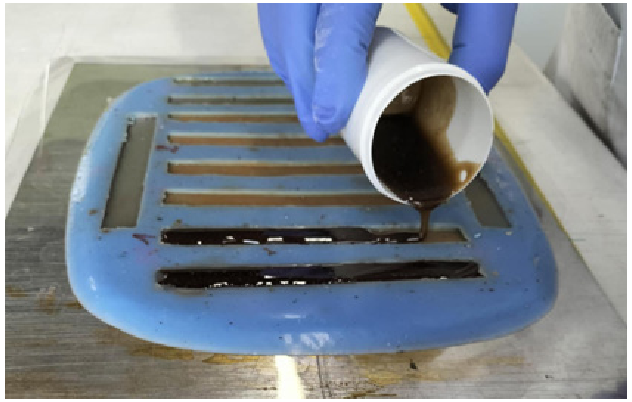
For many composite applications, such as those in transportation, electronics, or building materials, flame-retardant (FR) properties are essential. Conventional flame-retardant strategies often rely on the incorporation of solid additives such as ammonium polyphosphate (APP) or aluminum trihydroxide (ATH). Although effective, these solid fillers present several drawbacks: they can significantly increase viscosity, hinder resin flow in processes like resin transfer molding (RTM) or vacuum infusion, or lead to incomplete fiber wet-out. Liquid flame retardants can mitigate some of these processing limitations by preserving low resin viscosity; however, they typically function as plasticizers. This results in substantial reductions in glass transition temperature (Tg) and thermo-mechanical performance, rendering them unsuitable for structural automotive composite applications where thermal stability and mechanical integrity are essential.

Development objectives

The primary objective of this work was to develop and validate a flame-retardant resin system achieving a UL-94 V-0 rating while maintaining a glass transition temperature (Tg) preferably above 100 °C, in order to meet the requirements of structural automotive composite applications.
To this end, a flame-retardant solution was specifically designed for the best perfoming bio-based expoxy resin from the SUSPENS project (PHTE/MPA), targeting the typical trade-offs between fire performance, processability, and thermo-mechanical properties. The selected flame-retardant component is solid at room temperature, thereby reducing significantly the plasticization effects commonly associated with liquid flame-retardant additives, yet melts at elevated processing temperatures, enabling homogeneous incorporation without adversely affecting resin flow or impregnation behavior. Final formulation optimization was achieved through the addition of a bio-based reactive diluent, further improving processability while preserving thermal performance and reinforcing the overall sustainability profile of the system.

Key target KPIs:

- UL-94 flame-retardancy rating: V-0
- Glass transition temperature (Tg): > 100 °C
- Compatibility with RTM and vacuum infusion processing
- Retention of bio-based content and sustainability credentials



Flame-retardant resin formulation

Samples for UL94V test

Approach & methodology

To address the identified challenges, a novel flame-retardant strategy was developed based on the combination of resorcinol, which can be sourced from bio-based feedstocks, with a tailored organophosphorus compound. This combination was designed to deliver effective flame retardancy while maintaining the thermo-mechanical performance required for structural composites.
The resulting flame-retardant system was incorporated into the bio-based expoxy resin from SUSPENS (PHTE/MPA) at varying concentrations to identify the optimal formulation. The evaluation focused on achieving a balance between high flame-retardancy performance (targeting UL-94 V-0) and minimal impact on glass transition temperature (Tg).
In parallel, resin viscosity and flow behavior were systematically assessed and optimized to ensure compatibility with liquid composite manufacturing processes such as RTM and vacuum infusion. Processability was further fine-tuned through formulation adjustments, enabling efficient impregnation and fiber wet-out without compromising flame retardancy or thermal performance.

Key findings

The optimized formulation demonstrated a low viscosity of 365 cP at 80 °C, confirming its suitability for liquid composite processing techniques such as RTM and vacuum infusion. The system achieved a UL-94 V-0 flame-retardancy rating, meeting stringent fire-safety requirements, while maintaining a glass transition temperature (Tg) of 108 °C, well above the target threshold for structural automotive composites.

These results confirm that effective flame retardancy can be achieved without compromising processability or thermo-mechanical performance, overcoming the typical trade-offs associated with conventional solid or liquid flame-retardant systems. The formulation has been validated at laboratory scale, corresponding to early experimental demonstration (TRL 3), and provides a strong basis for further scale-up and composite-level validation.

UL94V test without flame retardant (sample completely burnt)

After UL94V test with flame retardant

Effective flame retardancy can be achieved without compromising processability or thermo-mechanical performance.

Impact & added value

The developed flame-retardant bio-based resin system represents a promising advancement toward fire-safe, high-performance composite materials, addressing a key limitation in balancing flame retardancy, thermo-mechanical performance, and processability. The demonstrated combination of UL-94 V-0 flame retardancy and a glass transition temperature of 108 °C indicates strong potential for use in structural composite applications, particularly in automotive and transport sectors, where fire safety and thermal stability are critical.

From an industrial perspective, the results indicate a high degree of manufacturing relevance at laboratory scale. The formulation exhibits low viscosity (365 cP at 80 °C), compatible with liquid composite manufacturing processes such as resin transfer molding (RTM) and vacuum infusion, while avoiding the excessive viscosity increases associated with conventional solid flame-retardant fillers. The melt-processable solid flame-retardant concept demonstrates the feasibility of achieving homogeneous dispersion without compromising resin flow, suggesting good prospects for future scale-up and composite-component validation.

Conclusions

In terms of sustainability, the approach aligns with the EU Green Deal and Circular Economy objectives through the incorporation of bio-based components. Validated at laboratory proof-of-concept level (TRL 3), the results provide a strong technical basis for progression toward TRL 4 and beyond, focused on expanded laboratory validation, composite testing, and preparation for industrially relevant process conditions.

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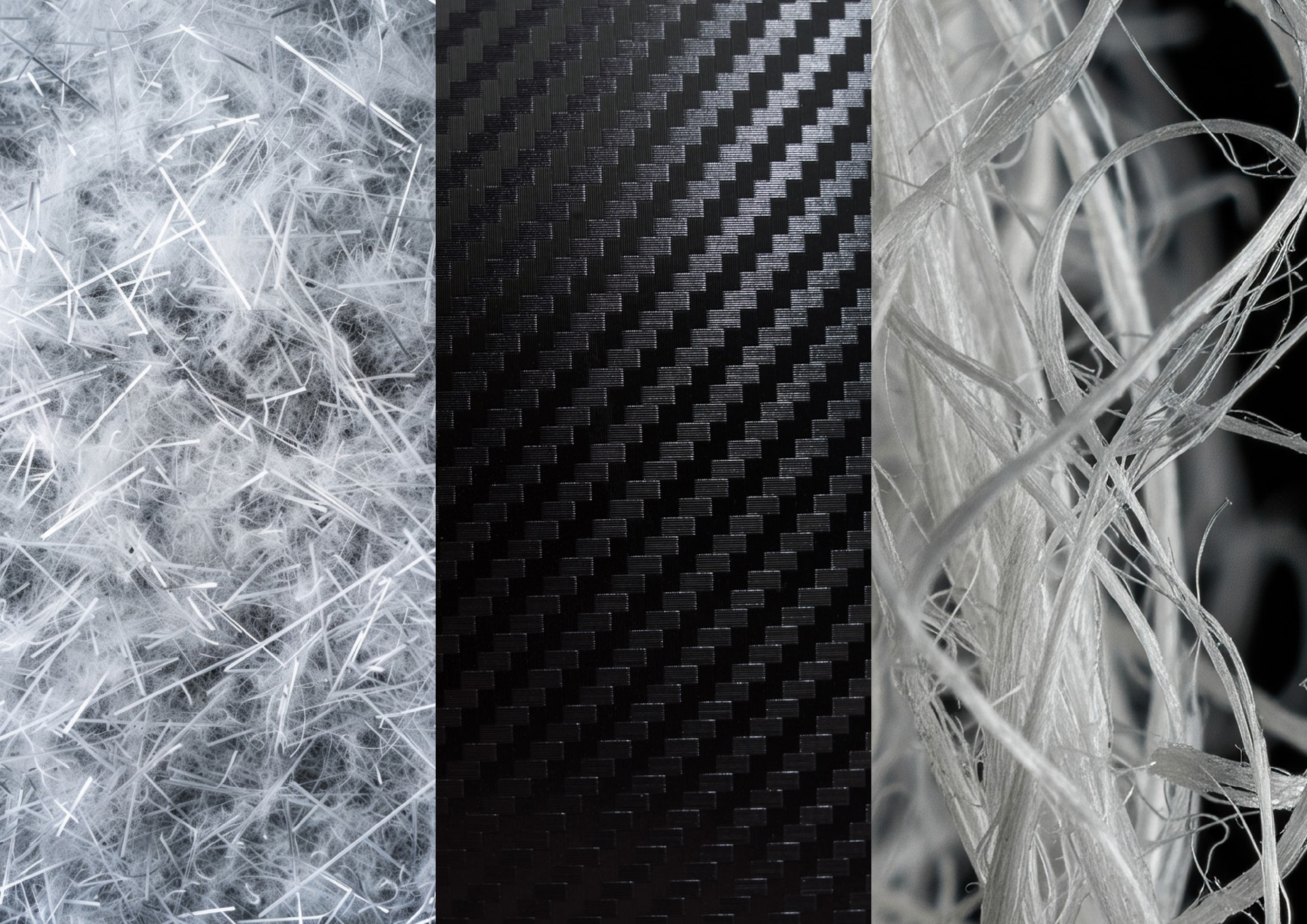


3

FIBERS.

The SUSPENS project has made significant advances in developing sustainable carbon fibers by recycling aeronautical waste and glass fibers from decommissioned wind turbine blades. Researchers have also explored high-performance natural fibers by processing cellulose and lignin, transforming these materials into eco-friendly alternatives for advanced applications.

By optimizing processes like melt spinning, stabilisation, and carbonisation, the team has achieved promising results in producing recycled carbon fibers with competitive mechanical properties. Additionally, the integration of bio-based precursors is opening new paths for greener manufacturing.

Through innovative techniques, the project has demonstrated the potential to exploit natural resources and upcycle waste into valuable resources, reducing reliance on virgin materials and foreign outsourcing.

3.1

Recycled glass fiber

Transforming end-of-life wind turbine blades into high-quality glass fibres for a circular economy

End-of-life wind turbines

Context & technical challenges

The wind energy sector faces a pressing environmental challenge with the disposal of decommissioned turbine blades. These blades, primarily composed of glass fibre-reinforced composites, are notoriously difficult to recycle due to their complex structure, where glass fibres are tightly embedded in resin matrices. As a result, the majority of these blades end up in landfills, contributing to significant waste accumulation and resource inefficiency. This issue is further exacerbated by the limitations of existing recycling methods, such as pyrolysis, which often degrade the mechanical properties of the fibres due to high-temperature processing. Such methods typically result in downcycling, where the recycled material is of lower quality and can only be used in less demanding applications, such as fillers.

Development objectives

The primary objective of this project was to develop and validate a circular recycling process specifically designed for glass fibres extracted from end-of-life wind turbine blades. The goal was to demonstrate that these recycled fibres could achieve mechanical properties comparable to those of virgin fibres, with a particular focus on tensile strength, which is a critical performance indicator for composite materials. By doing so, the project aimed to avoid the pitfalls of downcycling and instead enable the production of high-quality, recycled glass fibres suitable for demanding applications.

A key target was to design and implement a pilot plant capable of processing between 50 to 100 tons of fibres annually. This pilot plant would serve as a proof of concept, demonstrating the scalability and economic viability of the recycling process. The project also sought to optimize energy and water consumption while minimizing labour costs, ensuring that the recycled fibres could compete with virgin materials in terms of both performance and cost.

Approach & methodology

After evaluating several potential partners to reclaim glass fibres from end-of-life wind turbines, WH Lipex selected a company that utilized an innovative, non-thermal cleaning method based on pulse and frequency technologies. This approach effectively removed contaminants from the fibres without exposing them to high temperatures, thus preserving their mechanical properties. Lab-scale tests were conducted to validate this method, beginning with the production of fibres from virgin materials to establish a benchmark. Subsequently, 2.5 kg of fibres extracted from actual decommissioned blades were purified, remelted, and drawn into new fibres. The results confirmed that the recycled fibres exhibited tensile strength and melting characteristics comparable to those of virgin fibres.

The next phase involved designing a pilot plant to scale up the process. This plant was conceived as a modular system, starting with a batch process for fibre separation and cleaning, followed by continuous melting and fibre drawing. The furnace, a critical component of the plant, was designed to be gas-fired, with considerations for incorporating platinum lining to reduce heating and cooling times, although cost constraints posed a challenge. The fibre-forming station was designed to be adjustable and transportable, allowing for flexibility in testing and optimization.

16 kg of recycled fibre produced

→

70 linear meters of fabric for demonstration purposes

Glass pellets made from recycled glass

Key findings

Lab-scale and pilot-scale tests demonstrated that the recycled glass fibres exhibited tensile strength within 5% of that of virgin fibres, confirming that the mechanical properties were preserved. Additionally, the melting temperature and visual properties of the recycled fibres were indistinguishable from those of standard fibres, further supporting the success of the process.

The purity of the recycled fibres was another critical outcome, with residual contaminants reduced to less than 1%, making them suitable for high-quality applications. The project achieved a Technology Readiness Level (TRL) of 6, indicating that the technology has been successfully demonstrated in a relevant environment and is ready for pilot-scale implementation. However, challenges remain, particularly in optimizing energy consumption and addressing the variability in glass types used in older turbine blades. These variations can affect the consistency of the melting process and require further refinement. Despite these challenges, the project has laid a solid foundation for scaling up the recycling process and integrating it into industrial production.

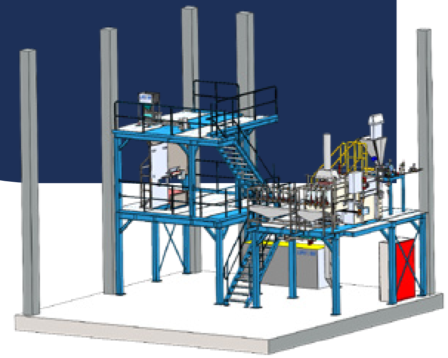
Melting furnace

> *The recycled glass fibres exhibited tensile strength within 5% of that of virgin fibres, confirming that the mechanical properties were preserved.*

Weaving of recycled glass fiber

Impact & added value

From an industrial perspective, the project establishes a scalable and modular pilot plant design that can be expanded to process over 1,000 tons of fibres annually with additional investment. This creates potential for job creation in recycling facilities and composite manufacturing, while also reducing the reliance on virgin materials. The pilot plant's flexibility and transportability allow it to be deployed in various locations, further enhancing its industrial applicability.



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3.2 Recycled carbon fiber

Recycled carbon fibre (rCF) staple yarn made from post-industrial waste

Context & technical challenges

The production of carbon fibre (CF) is an energy-intensive process, relying heavily on petroleum-derived precursors like polyacrylonitrile (PAN). Despite its exceptional strength-to-weight ratio, which makes it indispensable in aerospace, automotive, and renewable energy sectors, a significant portion of CF (up to 30-40% in aerospace) ends up as waste each year. This waste stems from offcuts, defective parts, and end-of-life components, often discarded due to the lack of cost-effective recycling solutions. CF production consumes vast amounts of fossil fuels and energy, yet much of the material is landfilled or incinerated, squandering its embedded value. Addressing this challenge requires innovative recycling technologies and collaborative supply chains to reclaim and reprocess CF waste, turning it into a viable resource for new composites and closing the material loop.

Development objectives

The project focused on developing a recycled carbon fibre staple yarn from aeronautical production waste. Carbon fibre fabrics, used extensively in aerospace, generate up to 30% scrap during cutting for part manufacturing. These offcuts, typically discarded, were recovered and transformed through a dedicated process into a carded staple yarn (a continuous yarn made from discontinuous scrap fibres).

This innovation enables the reuse of carbon fibre waste, reducing reliance on virgin materials while maintaining structural integrity. By transforming scrap into a value-added product, the SUSPENS project advances sustainability and circularity in the composites industry, offering a scalable solution for high-performance applications.

In the SUSPENS project, the primary goal was to increase the carbon fibre content in recycled staple yarns. Previously, staple yarns produced from recycled carbon fibres were limited to a maximum of 60% carbon content, as they relied on blending carbon fibres with polymeric filaments (e.g., polyamide) to produce a processable yarn.

Our ambition was to develop a staple yarn containing over 90% carbon fibre, restoring mechanical properties close to those of virgin carbon fibre. Additionally, we focused on maximizing the alignment of carbon fibres within the yarn, a critical factor for achieving high performance.

Approach & methodology

The work conducted in the SUSPENS project was subconctracted and carried out by ***the ITM (Institute of Textile Machinery and High-Performance Material Technology)*** at the Technical University of Dresden.

STEP 1: Sourcing carbon fibre waste

Two types of carbon fibre waste were considered:

- **Post-consumer waste:** Recycled fibres obtained through resin and matrix separation from end-of-life composites. These fibres were produced by both solvolysis and pyrolysis route. However, a key challenge was the need for re-sizing (reapplying a surface treatment) to enable the spinning process. Unfortunately, few facilities currently have the capacity to process and re-size sufficient quantities (tens to hundreds of kilograms) of these fibres. The limited samples obtained from various suppliers were not of adequate quality for transformation into staple yarn.
- **Post-industrial waste:** Cutting scraps directly recovered from the aeronautical industry. This waste was selected for further development due to its higher quality and availability.

STEP 2: Fibre selection and processing

Several references of discontinuous carbon fibres were sourced from Procotex France and studied by the ITM laboratory. A specific format was chosen to initiate the spinning process.

STEP 3: Modifications to spinning and carding lines

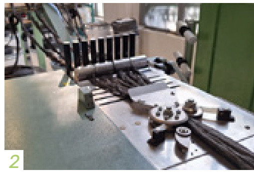
Adjustments were made to the carding and spinning lines at ITM to improve the quality of the sliver (a loose rope of fibres) and maximize the carbon content in the yarn.

STEP 4: Staple yarn manufacturing process

The process for producing carded staple yarn involves three main steps:

- **Carding[1]:** Fibres are processed through carding rollers, thus realigned and agglomerated into slivers.
- **Drawing[2]:** Slivers are elongated and stretched to further align the fibres, optimizing mechanical properties.
- **Spinning[3]:** The drawn slivers are spun to reduce their cross-sectional volume. A polyamide guiding filament is used, with careful attention to limit its use to a maximum of 10% to ensure the final yarn contains over 90% carbon fibre. This approach successfully increased the carbon fibre content in the staple yarn, bringing mechanical properties closer to those of virgin carbon fibre.

1



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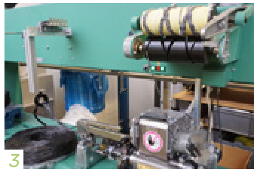

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Key findings

The key results achieved in this project include the successful upgrade and modification of the spinning line at ITM, where specific components were improved to enhance the quality of the feed material.

Main achievements:

- **Successful production of carded staple yarn** from carbon fibre waste sourced from aeronautical composite manufacturing plants.
- **The waste material was supplied by an industrial-scale provider and transformed into 20 kilograms of carded yarn** with a carbon content exceeding 90%, specifically 92%. The remaining 8% consists of a polyamide guiding filament, used primarily for yarn wrapping.
- 

  The produced yarn has a linear density of 1500 tex, making it compatible with conventional carbon reinforcement manufacturing processes, including weaving and fabric production.

Demonstration and validation:

- **The yarn was successfully used to produce reinforcements** via Tailored Fibre Placement (TFP) at IRT Jules Verne, creating oriented reinforcements at 0° and 90°.
- **These reinforcements were subsequently used to manufacture panels and parts** using the Resin Transfer Molding (RTM) process.
- Composite panels made from the project staple yarn and a standard aerospace resin shown a 50% drop of tensile properties versus a standard and virgin carbon fibre. This is due the discontinuity and a misalignment of the fibres inside the yarn. This could be further improved with additional work and should be continued.

This breakthrough demonstrates the feasibility of high-carbon-content recycled yarns for industrial applications, significantly advancing sustainability in composite manufacturing.

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Impact & added value

The product developed in the SUSPENS project transforms industrial carbon fibre waste into a continuous yarn that can be processed using conventional composite manufacturing methods. The yarn properties remain significantly lower that those of virgin carbon fibres, but further optimisation is reachable by working on the alignment of discontinuous fibres within yarn during the drawing phase of the sliver.

Key areas for improvement:

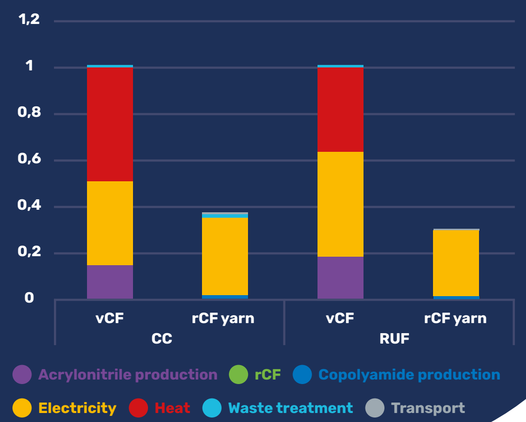
- **Fibre alignment:** Future work should focus on enhancing the alignment of carbon filaments within the yarn, as the current performance drop is primarily attributed to this issue.
- **Supply chain security:** To enable industrial-scale production, it will be essential to secure a stable supply of carbon fibre scrap. While several initiatives currently aim to exploit these waste streams, ensuring an adequate and consistent supply will be critical for large-scale yarn production.

This project lays the foundation for a sustainable and scalable solution for recycled carbon fibre, but further optimization and supply chain development are needed to fully realize its industrial potential.

Environmental impact:

Life Cycle Assessment (LCA) studies indicate that the environmental footprint of these carded yarns is reduced by 62% compared to virgin carbon fibre yarns, for every 100 kilograms produced.

Impact on Climate change & Fossil resources use of rCF vs vCF (normalised values)



3.3 Cellulose fiber

This article tells the story of how everyday cotton roll towels—used and washed—were transformed into new, strong continuous filaments for composite production. It explains why this matters for people and the planet, how the process works in practice, and what the results mean for the future to establish a circular economy.

Why does this matter?

- **Textile waste is rising worldwide.** Even natural fibers like cotton take a serious environmental burden in farming and finishing, so keeping cotton in circulation longer is important. The European Parliament highlights the need to reduce textile waste and promote material circularity.[1]
- **Most "recycling strategies" of cotton today weakens fibers;** the output is often downcycled into lower value products or blended with virgin or synthetic fibers. True fiber to fiber upcycling remains rare.[2]
- **Replacing glass and carbon fibers with natural fibers** within composite applications helps cutting energy and CO2. Natural fibers are renewable feedstocks offering low density and good specific stiffness.[3]

What was our approach?

This work demonstrates a practical route from postconsumer towels to regenerated continuous cellulose filaments with high strength for composite application—evidence that circularity can be both feasible and of high quality.[2, 4] Cotton roll towels—white (preconsumer and postconsumer)—were collected and combined to mimic real waste streams. Using towels that had lived different service lives captures

the variety in use, finishes, and dyes that recyclers are facing. In simple terms, cotton waste—not pristine lab cotton—was used to answer the following question: Can the Ioncell® process be used to produce high-quality new fibers and filaments from it?

What is the Ioncell® process?

Compared with commercial fiber spinning methods, the Ioncell® process is a gentler chemical recycling route that enables upcycling in terms of fiber strength. Cellulose is dissolved in superbase based ionic liquids—such as 1,5 diazabicyclo[4.3.0]non 5 enium acetate ([DBNH][OAc]), 7 methyl 1,5,7 triazabicyclo[4.4.0]dec 5 enium acetate ([mTBDH][OAc]), or 1,8 diazabicyclo[5.4.0]undec 7 enium acetate ([DBUH][OAc])—at 80–95 °C, then spun into fibers at similar or lower temperatures and regenerated in cold water (≤12 °C). Ioncell fibers belong to the Lyocell family. Conventional Lyocell uses N methylmorpholine N oxide (NMMO), a direct solvent with known stability issues. NMMO based fibers typically show moderately lower tenacity than fibers produced with superbase based ionic liquids, while exhibiting similar elongation.[5]

What are the results?

Before usage, the cotton was grinded and cleaned via gentle acid wash using dilute sulfuric acid solution. The degree of polymerization (DP) was adjusted to meet the requirements of the technique (DP range: 900 – 1200) and further to ensure smooth, trouble free fiber spinning.[4, 6] The cotton was mixed with [DBNH][OAc] forming the dope, a cellulose – ionic liquid spinning solution. The solution was extruded through a fine 400 hole spinneret using a dry jet wet spinning setup. Filaments were drawn at draw ratios (DR) 11, washed in water, and dried—producing smooth, circular regenerated continuous cellulose fibers *(Figure 1)*.[5] In total, 1 km of fiber was manufactured. Three spinning runs were combined to obtain a single bundle (tow) with a filament count of 1200.

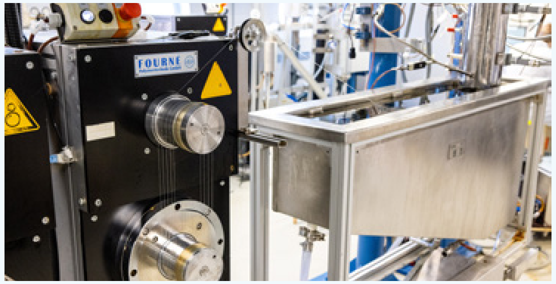
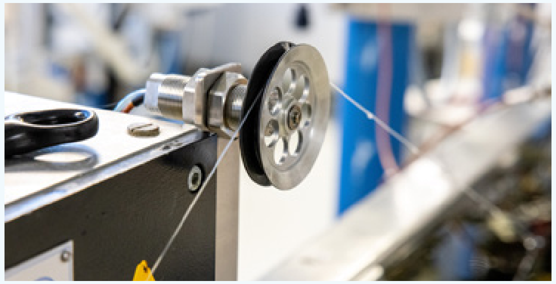


Figure 1: Illustration of the continuous fiber processing via the Ioncell® technique.



The fibers were delivered to the IRT Jules Verne for the production of composite materials.

60 single specimens have been tested showing an elongation of 9 ± 1 %, tenacities of 795 ± 60 MPa (53 cN/tex), a Young's modulus of 24 GPa and a toughness of 45 MPa.

The reported values approach the tenacity ranges of approximately 50 to 130 cN/tex for carbon fibers and exceed their extension at break (0.3 – 2.0 %).[7] However, the properties are significantly below the performance of glass fibers (2400 – 3500 MPa tensile strength, 4.0-5.4% elongation at break).[8]

The impact of fiber linear density and tenacity on the composite properties have been studied by means of a lab scale unidirectional vacuum infusion mold system *(Figure 2)*. Both parameters do not affect the mechanical properties of the composites dramatically. However, a higher fiber strength positively influences the composite strength. A tremendous increase in linear density affects the handleability and mechanical performance negatively leading to matrix failures, which weakens the composites. Compared to similar composites reinforced with commercial cellulose-based filaments (viscose), the Ioncell® composites made from recycled cotton towels were highly competitive reaching slightly higher composite strength values despite of similar fibre tenacities.

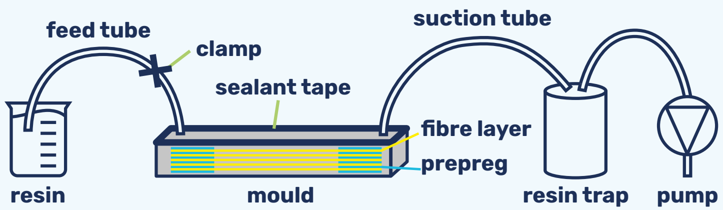


Figure 2: Illustration of the unidirectional vacuum infusion mold system.

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Conclusions

This process transforms mixed, real-world cotton towel waste into new, robust continuous fibers (true upcycling) without blending with virgin or synthetic fibers. The resulting yarns surpass those derived from the original towels and are comparable to or exceed existing literature values.[2] Regenerated fibers have been integrated into composites demonstrating a real-world application scenario. This represents a crucial step toward industrial applicability. Maintaining cotton in the production cycle can diminish the demand for virgin fiber and reduce the environmental impacts associated with cultivation, processing, and disposal—objectives that align with European policy priorities concerning textile waste and circular economy.

3.4 Lignin-precursor & carbon fibers

Sustainable carbon fiber precursors produced from lignin-biopolyamide blends

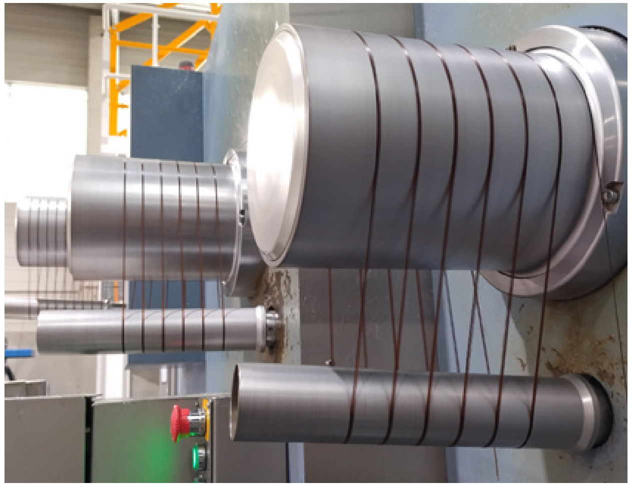
Context & technical challenges

Lignin is a naturally occurring polymer that forms a key structural component of plants, binding cellulose fibers to provide strength and rigidity. As the second most abundant plant-derived material after cellulose and rich in carbon, lignin is gaining interest for sustainable development, particularly as a renewable feedstock for carbon-fiber precursors in lightweight, high-performance applications.

Lignin-based fibers can be produced using techniques such as melt spinning, solution spinning, and electrospinning. Among these, melt spinning is particularly attractive because it is fast, cost-effective, and solvent-free, reducing both environmental impact and production costs. For industrial processing, lignin is often blended with other (bio-)polymers to improve processability and scalability. Polymers such as polylactic acid, thermoplastic polyurethane, and polyethylene terephthalate have been investigated, though each presents challenges related to compatibility, spinnability, and conversion into carbon fibers. Polyamides (PA) are another promising option, as their ability to form hydrogen bonds makes them quite compatible with lignin. While earlier studies demonstrated the potential for melt-spun PA-lignin fibers, further optimization is still required.

Development objectives

In SUSPENS, the research on PA-lignin blends production was continued, with focus on novel biobased polyamides, more specifically polyamide 5.10 and 5.13, which blend more easily with lignin. The project also used hydrolysis-type lignin derived from European hardwoods to support sustainability and regional sourcing. Alongside material development, the research aimed to refine processing conditions to create improved precursor fibers and to determine the most effective way to stabilize them before they are converted into carbon-based fibers.



Yarn drawing during melt-spinning process

Approach & methodology

Polyamide and lignin were first blended in equal amounts using a compounding process to create a uniform material. This blend was then transformed into fibers through melt spinning, a process in which the heated material is forced through fine openings to form thin filaments. As the filaments emerge, they are cooled by air, stretched over a series of heated rollers to improve their strength and structure, and

Precursor fiber bobbins

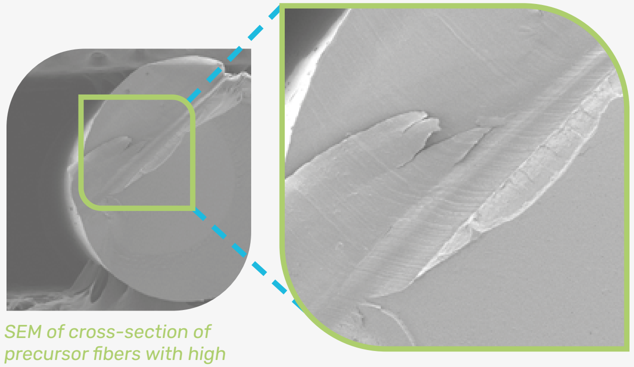
finally gathered and wound into continuous filament bundles. To ensure stable processing and good fiber formation, the blends were diluted with pure polyamide. This resulted in fibers containing around 45% lignin while maintaining good spinnability. Different types of lignin were used, each with varying structural characteristics (specifically the content of β-O-4 linkages), to study how these differences influence processing and performance.

The resulting materials and fibers were thoroughly characterized to assess their properties. This included analyzing their thermal behavior (such as glass transition, crystallization, and melting temperatures), chemical structure, morphology, and mechanical performance. Together, these evaluations provided insight into how well the materials mix and how suitable they are for producing strong, high-quality fibers.

Pilot-scale melt-spinning line (Spinmaster)

Key findings

By combining microscopy analysis with material and mechanical testing, the study shows that PA5.13 is the best-performing polyamide for blending with lignin, as it mixes more evenly with the material. In addition, lignin with a higher β-O-4 linkage content (22.2% vs. 14.8%) further improves material properties and compatibility, including how well the material can be processed into fibers. This good mixing behavior is clearly visible in microscopy images. When the β-O-4 linkage content was very low (12.4%), fiber spinning was no longer possible.



SEM of cross-section of precursor fibers with high Β-O-4 linkage content

For yarns containing 45% lignin with a β-O-4 linkage content of 14.8%, a tensile strength of 0.105 ± 0.004 N/tex and a stiffness (E-modulus) of 2.48 ± 0.05 N/tex were achieved. When lignin with a higher β-O-4 linkage content (22.2%) was used, the yarns showed a slightly higher tensile strength of 0.114 ± 0.006 N/tex and a similar stiffness of 2.48 ± 0.09 N/tex. The yarn thickness ranged from 87 to 101 tex. These findings support the applicability of lignin–PA5.13 blends at a semi-industrial melt-processing level, corresponding to TRL 5-6.

Impact & added value

This study shows that lignin-based biopolyamides (PA5.13) can be successfully processed by melt spinning, a widely used industrial fiber-manufacturing technique. This confirms lignin's potential as a renewable alternative in fiber production. The results expand the range of achievable material properties, enabling lignin-rich fibers that can serve as precursors for carbon fibers and other functional applications. Future work will focus on converting these precursor fibers into carbon fibers and exploring compatible lignin blends for melt-spun products, for example fibers with flame-retardant (FR) properties. **From an industrial and environmental perspective, compatibility with established melt-spinning processes supports scalable manufacturing, while the use of lignin, an abundant bio-based by-product, helps reduce reliance on fossil-based polymers and supports the development of more sustainable fiber solutions.**

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4 DEMONSTRATORS.

The materials developed in SUSPENS have been processed into composite panels and demonstrator parts for testing and benchmarking against commercial references.

For the automotive sector, battery-pack base plates and top covers have been successfully manufactured, achieving a UL 94 V0 fire rating and meeting mechanical performance standards.

The boat demonstrator has showcased a sailboat deck made from sustainable resins and fibers, validated for marine aging resistance, and has demonstrated the possibility to substitute current materials with recycled glass fibers and bio-resins to support circular economy goals. In aerospace, a hollow one-shot composite part has been produced using recycled carbon fibers, eliminating assembly steps and advancing sustainable manufacturing. Overall, SUSPENS has highlighted the potential of innovative, eco-friendly materials for high-performance applications.

4.1 Automotive use case

Bio-based SMC material for a battery-case top-cover of an e-scooter

Context & technical challenges

For over 40 years, COMPOSITEC has been a trusted expert in composite technologies, delivering high-performance, lightweight, and cost-efficient parts from design to production. As mobility shifts toward circular and sustainable materials, composite solutions must evolve too. A key material in the automotive sector—Sheet Molding Compound (SMC)—is typically made from unsaturated polyester resin, glass fibers, fillers, and additives. However, current SMC formulations rely on petroleum-based polyester and high levels of styrene, a volatile compound that generates significant emissions during storage and molding. This raises increasing challenges for compliance with VOC regulations and REACH.

Development objectives

Within the SUSPENS project, Megara Resins explored bio-based alternatives to petroleum-derived polyester and styrene, as well as new reactive diluents. The initial KPIs targeted highly sustainable resin systems—up to 95% bio-based UPR, using non-toxic reactive diluents, and delivering a Tg above 100 °C. Additional requirements such as fire resistance, fluid stability, and other end-user compliance needs were also investigated.

Approach & methodology

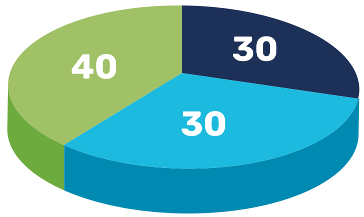
Megara Resins investigated several bio-based resins and combinations of alternative reactive diluents to replace styrene while still meeting performance targets.

A trade-off was identified: bio content could be increased up to 51%, and styrene reduced by 50%, while the resulting glass transition temperature was limited to 60 °C, below automotive expectations.
The selected SUSPENS resin was formulated into an SMC compound tailored with fire-retardant additives, a key requirement for the targeted top cover application addressed as a demo case. This SMC is called "SMC SUSPENS resin".

In parallel to SUSPENS work, COMPOSITEC has screened bio-based product from their existing SMC suppliers to evaluate state-of-the-art solutions. One material reference was selected from the company IDI as a benchmark for bio SMC and called "Benchmark Bio-SMC".

Below is a standard repartition of each ingredient in the SMC formula, where UPR matrix accounts for 30% of the total material (wt%).

SMC standard composition (%)



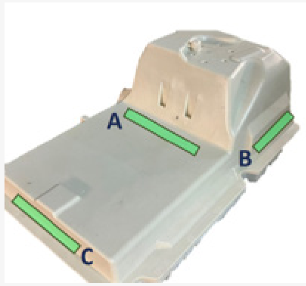
SMC	BIO DILUENT	BIO CONTENT IN RESIN + DILUENT PART (%)
SMC SUSPENS resin = SUSPENS bio-SMC including 100% Megara resin	**Yes** 50% IBOMA and 50% styrene	**23,2%** Resin and diluent contributions
SMC 50% SUSPENS resin = SUSPENS bio-SMC including 50% Megara resin – 50% benchmark resin	**Yes** 50% IBOMA and 50% styrene	**23,6%** Resin and diluent contributions
SMC benchmark with bioresin = Benchmark bio-SMC	**No** only styrene	**23,6%** Only resin contribution
SMC production = Standard SMC	**No**	**0**

Combinations of ingredients tested in the project

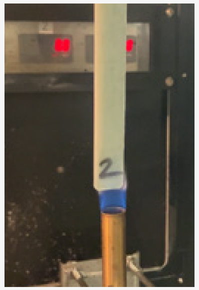
Material processing has been demonstrated on flat panels before producing top cover demonstrators. ***Note:*** *for processability issue it was not possible to mold top cover with bio-SMC including 100% SUSPENS resin. A trade-off SMC called "**SMC 50% SUSPENS resin**" including 50% MEGARA resin – 50% benchmark resin was created.*

Key findings

Loading plan for SMC with 50% SUSPENS resin used for demonstrator molding:



Test specimens have been taken from molded parts ↑ according to the picture above.

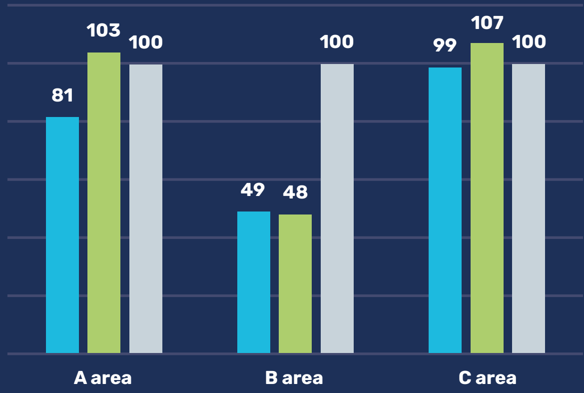


Regarding the fire behavior, both bio-SMC materials reach the target of V0 ranking, compliant with UL94 protocol:

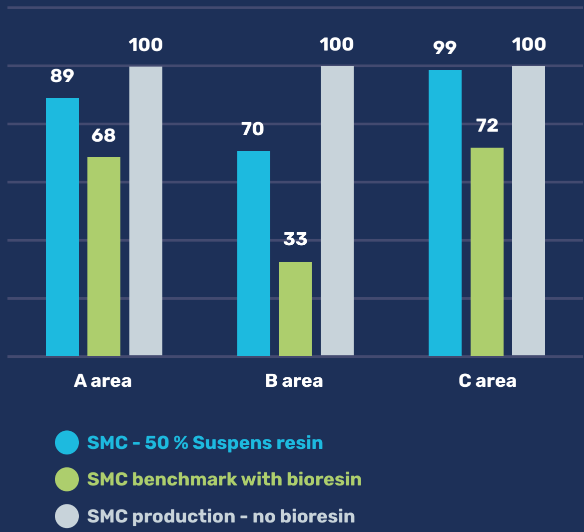
	BENCHMARK BIO-SMC	SUSPENS BIO-SMC
UL 94 V	V0 at 3,2mm	V0 at 3,2mm

Mechanical results obtained on bio-SMC from SUSPENS and benchmark are presented below:

Tensile strength on bio-SMC vs reference = standard SMC



Tensile modulus on bio-SMC vs reference = standard SMC



Bio-SMC with SUSPENS resin shows good results on A and C areas in comparison to the reference. Area B however, is weaker with SUSPENS and benchmark bio-SMC.

Impact & added value

The SUSPENS project enabled COMPOSITEC to learn more SMC formulations using bio-based resins and reduced styrene.
While none of the developed solutions fully meet automotive requirements, this work clarified the key factors driving the inclusion of bio-resin in SMC compound and their involvement on part performance. **With emerging bio-based UPRs and lower styrene systems, COMPOSITEC sees real potential for more sustainable SMC and will continue collaborating with its suppliers to increase the share of greener materials offered to customers.**

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4.2 Sailing boat use case

Context & technical challenges

The transition to sustainable composites faces major technical challenges. Traditional methods are energy-intensive and inefficient, often requiring multiple curing and assembly steps. Key challenges include:

- **Multiple process steps:** Manufacturing sandwich structures (e.g., boat hulls) involves multiple bonding and infusion stages, increasing defects and material waste.
- **Energy consumption:** The ambition is to adopt « one-shot » technology (single molding) to reduce energy use by eliminating repeated curing cycles.
- **Durability and protection:** Bio-based or recycled composites may degrade in marine environments. The challenge is ensuring resistance to aging and chemical compatibility with protective primers.

In short, the focus is on reducing costs and environmental impact while maintaining structural integrity and longevity.

Development objectives

The objectives of this activity were to validate a new generation of nautical components, transforming sustainable materials into competitive products. Key points and KPIs include:

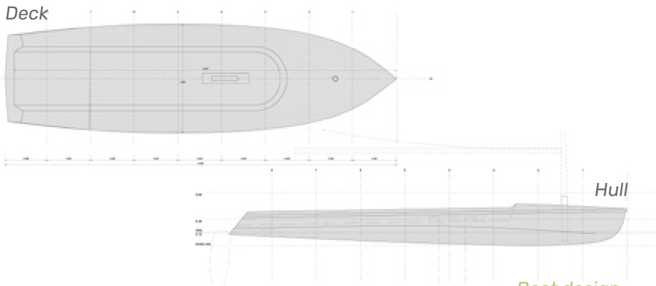
- **Efficiency and performance:** Achieve a 25% weight reduction in the deck to improve fuel efficiency and maneuverability, and reduce production costs by 25% through the one-shot process.
- **Innovation in materials:** Validate the combination of bio-based resins with recycled glass fiber (rGF).
- **Circularity and knowledge protection:** Expand industrial expertise from construction to end-of-life recycling and protect intellectual property through trademarks and industrial design.
- **Commercial exploitation:** Introduce new sailboats and maritime products using lightweight, renewable materials, positioning APM as a leader in eco-friendly nautical solutions.

Approach & methodology

The methodological approach following an engineering workflow, starting from material validation on a small scale to testing in a real environment (sea trials), is detailed hereafter.

1 Mold design and preparation of industrial adaptation

The process began with the design and prototyping of the sailboat, daggerboard, and rudder. Final molds specific to the deck and hull with side flanges were manufactured, an innovation necessary to optimize the vacuum infusion process and ensure watertightness.



Boat design

Final deck and hull molds

2 Material experimentation and validation, lamination testing

Before final production, various composite laminate samples were tested. These tests combined the new resins (epoxy/polyester) with the continuous fibers developed in the project to verify chemical and mechanical compatibility, ensuring weight optimization.

Composite samples made with SUSPENS resins and fibers

3 Innovation in the manufacturing process

- **Functional prototyping:** The rudder and daggerboard served as an initial test piece to validate the behaviour of the SUSPENS resin under vacuum infusion, allowing adjustment of flow and curing parameters.

Rudder and daggerboard manufacturing under infusion process

- **Bio-sustainable integration:** The manufacturing of the final sailboat demonstrator used recycled glass fibers combined with a bio-based resin (UPR) developed in the project

4 Final validation (sea trials)

The methodology culminated in sea trials, where the sailboat has been tested under real dynamic conditions. This step was essential to validate not only the structural strength but also the durability of the new materials against maritime corrosion and UV rays.

Final prototype sea trial

Key findings

SUSPENS's main outcome has been the successful production of the sailboat deck using sustainable resins and fibers, with validated compatibility and resistance to marine aging.
The technology has been demonstrated in a relevant environment, with deck and components tested under real navigation conditions corresponding to a maturity level TRL6 (independently of the maturity of the sustainable materials used, which is lower).

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Impact & added value

The key benefits of the work carried out in SUSPENS are summarized below:

- **Material performance:**
  - Lightness without loss of stiffness: 25% weight reduction improves speed, draft, and stability.
  - Reliability of bio-resins: Sustainable resins withstand exothermic reactions in thick parts, matching traditional fossil materials in structural safety.
  - Use of rGF: Recycled glass fibers maintain mechanical properties for maritime applications and reduce dependence on volatile virgin fiber markets.
- **Industrial production:**
  - Smart hybridization: Combining rGF and bio-based resins lowers environmental impact while maintaining impact resistance.
- **Environmental benefits:**
  - Drastic carbon footprint reduction: Avoids energy-intensive virgin fiberglass production, cutting CO_2 emissions per kilogram of laminate.
  - Landfill diversion: Recycles traditionally non-recyclable fiberglass, reintroducing it into high-value applications like leisure boating.
  - Circular economy: Closes the loop, enabling boats made with rGF to be recycled in the future, fulfilling total sustainability goals.

4.3 Aerospace use case

Hollow demonstrator made from staple yarns and bladder-assisted RTM

Context & technical challenges

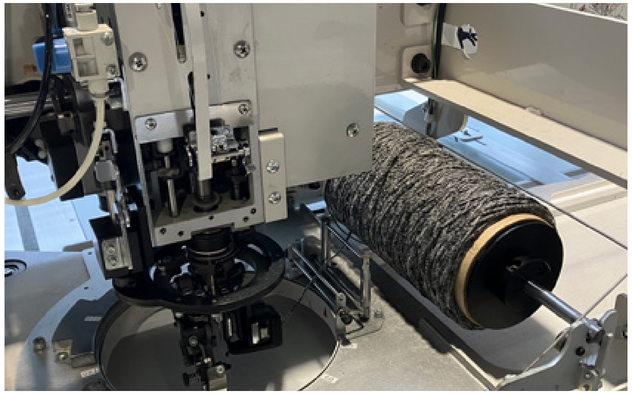
Recycled carbon fibers, often available as production waste, are difficult to integrate into high-performance applications due to their irregular properties and the lack of adapted manufacturing processes. Additionally, producing complex hollow composite structures typically involves high assembly costs, multiple fasteners, and drilling operations, which increases the environmental footprint. In this work, SUSPENS has addressed these challenges by exploring innovative ways to utilize recycled carbon fiber waste and develop an energy-efficient process that drastically reduces assembly time of complex structures.

Development objectives

The primary objective of this work was to demonstrate a viable manufacturing route for complex hollow composite parts using staple yarns made from recycled carbon fiber production waste.

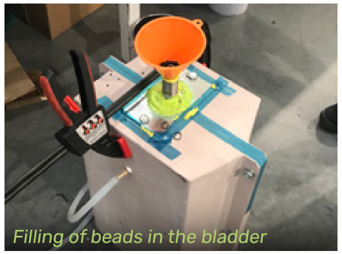
Key performance indicators included the demonstration that recycled carbon fibres can be transformed using the same process than virgin fibres, while maintaining a fiber volume fraction close to 50%. Additionally, the project sought to reduce the environmental impact by minimizing waste generation and energy consumption throughout the manufacturing process. The goal was to develop a process that could be scaled for industrial applications in sectors such as aerospace, automotive, and leisure boat manufacturing.

Approach & methodology



Tailored fibre placement of recycled staple yarns

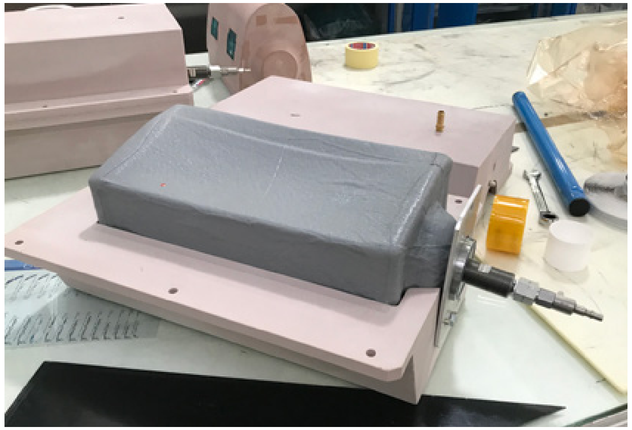
The methodology involved several innovative steps to address the technical challenges. First, carbon fibre production waste was transformed into staple yarns with a polyamide covering by the Institute of Textile Machinery (ITM), TU Dresden. These staple yarns were then used to manufacture preforms via Tailored Fiber Placement (TFP), a process that allows precise placement of fibers without generating scrap.



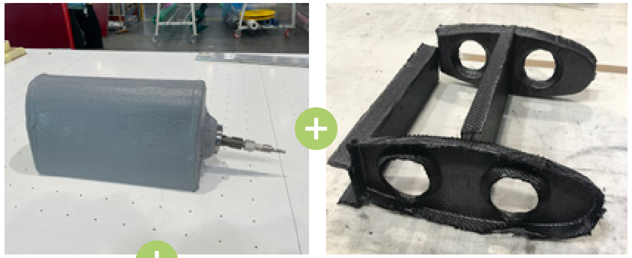
Filling of beads in the bladder

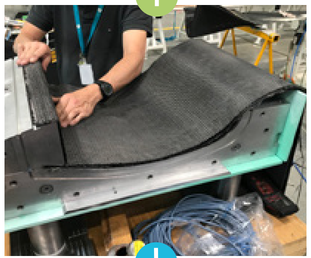
To produce complex hollow parts, a bladder-assisted Resin Transfer Molding (RTM) process was employed. This involved using reusable silicone bladders filled with polymer beads and water to apply uniform pressure during resin injection. An autonomous RTM tool was developed to manage both temperature and pressure, eliminating the need for complex and costly equipment like hydraulic presses. Flat panels were initially manufactured to validate process parameters and assess mechanical performance before scaling up to a hollow wingbox demonstrator. This approach ensured that the process was both energy-efficient and adaptable to various geometries.

Bladder manufacturing



Lay up sequence in the RTM mould





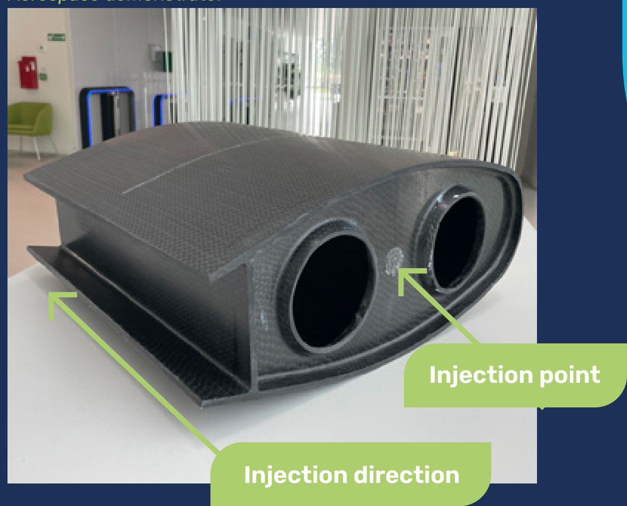
An energy-efficient process adaptable to various geometries.

Key findings

A hollow wingbox demonstrator was successfully produced using bladder-assisted RTM, validating the feasibility of the process for complex parts. The Technology Readiness Level (TRL) of the process was estimated at 4-5, indicating validation at the laboratory scale with potential for further industrial development.

Flat panels manufactured using staple yarns and RTM6 resin exhibited a tensile modulus of 22.4 ± 4.1 GPa and a flexural modulus of 11.7 ± 4.2 GPa. However, the fiber volume fraction achieved was approximately 40%, which was lower than the target of 50% due to the bulkiness and alignment issues of the staple yarns. Micrographs of the panels revealed large resin pockets and heterogeneous fiber orientation, which contributed to the lower mechanical properties compared to virgin fiber composites.

Aerospace demonstrator



Impact & added value

The bladder-assisted RTM process and autonomous tooling reduced the need for complex and expensive equipment, such as hydraulic presses, thereby lowering production costs and energy consumption. Environmental benefits were substantial: the TFP process generated no scrap, and the overall process chain reduced waste and energy use.

The integration of recycled materials contributed to a circular economy approach, reducing the reliance on virgin resources. **This work paves the way for more sustainable composite manufacturing, with potential applications in aerospace, automotive, and other industries seeking to lower their environmental footprint while maintaining high performance standards.**

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5 RECYCLING TECHNOLOGIES.

The SUSPENS project has focused on two innovative recycling processes for carbon fiber-reinforced polymers (CFRPs): solvolysis and pyrolysis. Solvolysis has been used to eliminate the resin from the composites developed within the project. Various solvents have been tested, and reclaimed elements have been used to produce new resins. Pyrolysis has been integrated into a novel pilot system that has combined continuous carbon fiber (CF) production from bio-based resources with simultaneous CFRP recycling.

A carbonization line has been connected to a semi-pilot pyrolysis furnace, where hot gases from carbonization have contributed to the pyrolysis of composite materials to reclaim fibers. This approach has reduced energy consumption by combining two energy-intensive processes into one, eliminating the need for additional inert gas and lowering the industrial environmental impact. Both methods have been assessed to define strategies for exploiting fibrous and liquid byproducts as secondary raw materials.

Novel pyrolysis approach

Innovative combined carbonisation-pyrolysis line for carbon fibers production and reclamation

Context & technical challenges

End-of-life thermoset composites usually end up in solid waste streams, i.e. they are burned or used as landfill. From the several available composite recycling technologies, pyrolysis is the most well-established one that enables the valorisation of fibres from the polymeric matrix.

Pyrolysis is a thermal recycling process that requires continuous feed of inert gas and considerable amounts of energy to achieve high temperatures (>500-800°C), considering also long operation time (i.e. 6 hours). The most energy-intensive step during the whole process is the heating of the pyrolysis furnace. The process energy consumption varies from 2.8 to 30 MJ per kg of Carbon Fiber Reinforced Polymer (CFRP) waste recycling, requiring new advancements for the energy and gas use reduction, while maintaining the properties and processability of the reclaimed fibres.

On the other hand, the production of carbon fibers (CFs) is also a high-energy-intensive process with consumption up to 704 MJ/kg of produced CFs, corresponding to CO_2 eq. emissions of 31 kg/kg of PAN. Fossil-based precursors, such as polyacrylonitrile (PAN), are thermally treated passing from a stabilisation and carbonisation process, to reach a fully carbonised state. During carbonisation process, the thermal treatment of the stabilised fibres is carried out at temperatures ranging from 1000 to 1800°C in inert atmosphere. The inert gas used (Nitrogen in most cases), together with the exhaust gas by-products, are usually burned in even higher temperatures, resulting in loss of energy. SUSPENS revealed the exploitation potential of the hot gas emissions of the carbonisation line of NTUA, to be used in the thermal decomposition of end-of-life polymeric composite matrices, through a novel combined pyrolysis pilot line (recovery of CFs and production of pyrolysis oils as secondary raw materials).

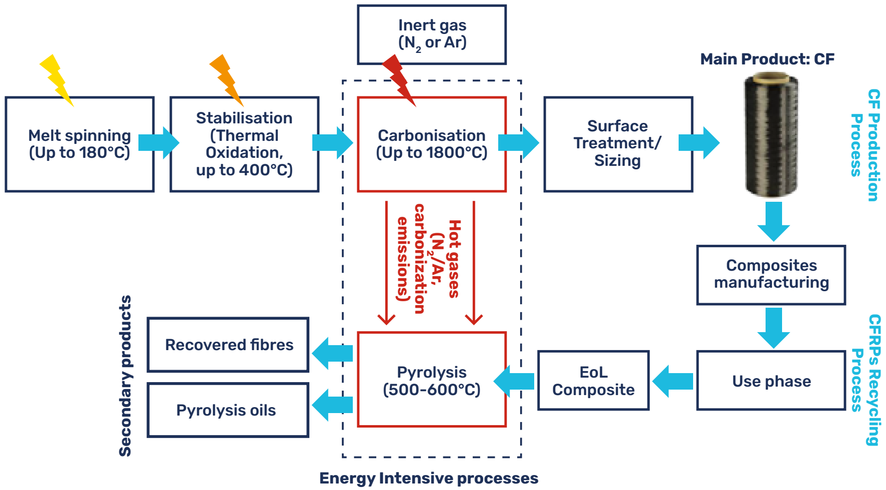
Development objectives

In SUSPENS, the **combination of the two processes (carbonisation and pyrolysis)** has been investigated targeting to reduce both the energy needed to heat the pyrolysis furnace, and the inert gas needed to maintain inert conditions, through the exploitation of the hot carbonisation gases. This way one energy-intensive process will be performed with reduced electrical consumption, leading to reduction of the CO_2 eq. emissions.

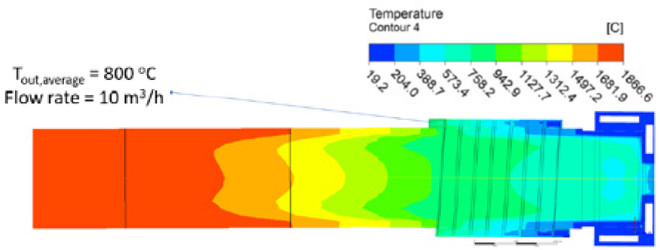
Approach & methodology

To realise this innovative pyrolysis line, 5 steps were followed:

- **CFD analysis of the heat and mass transfer for the two processes**
- **Design and modification of an existing pilot scale carbonization furnace** at NTUA to enable continuous CF production, including CFD analysis on heat distribution and transfer
- **Design of pyrolysis chamber** (assisted also with electrical supply)
- **Design of the connection between the two systems for efficient gases transfer**, including CFD analysis on the heat distribution from the carbonisation gases on the pyrolysis furnace
- **Manufacturing of the line**.



NTUA has the capacity to pyrolyse thermoset CFRPs at 550°C, thus the target was set to achieve this temperature with the assistance of the carbonisation hot gas, with reduced electrical consumption. The simulations showed that the hot gases at the edge of the carbonisation furnace could reach up to 800°C, thus the pyrolysis chamber that receives waste heat from the carbonisation line to reach the pyrolysis temperature of composites



(500-600°C) was designed. For the hot gases transfer, a coil was designed around the carbonisation furnace outlet to heat the gas before being transferred to the pyrolysis furnace.

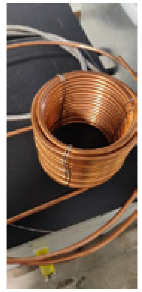
After manufacturing of the line, experimental investigation was performed to assess and validate the simulations and achieve hot gases transfer. Different coils were assessed for the gas transfer and respective gas flow rate was adjusted based on the gas temperature measurements.

Energy simulation models have been developed in Modelica by IRT Jules Verne to compare the performance of the initial line with that of the innovative line with the reuse of hot gases. These models required the creation of simulation components typically for representing carbonisation and pyrolysis furnaces. In addition, a more complex high-capacity industrial production line has also been modelled, incorporating ancillary systems such as an oxidation furnace and a regenerative thermal oxidizer for hot gas treatment.

In SUSPENS, carbonisation and pyrolysis were integrated to reduce energy consumption for furnace heating and inert gas demand by reusing hot carbonisation gases to maintain inert conditions.

Key findings

Based on the CFD calculations and expected pyrolysis temperature, the pyrolysis furnace constructed consisted by two main chambers; an inner and an outer one, separated by a layer of thermal insulation. At the back of the inner chamber the gas inlet and outlet have been placed. In case the inner chamber cannot be totally filled with the hot gases from the carbonisation line, extra inert gas will be introduced from a bottle, using supportive equipment for preheating this stream. A copper coil was used for gas transferring. With the carbonisation furnace operating at 1800°C, the distance between the 2 furnaces to be at 2 m, and a nitrogen flow to be above 300 ml/min, the



hot gases reaching the carbonisation furnace had reached 130°C (measured using a pyrometer). However, there was significant heat loss during transfer, thus insulation has to be improved to reach higher temperatures.

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Impact & added value

The preheated gases reaching the pyrolysis furnace will allow the reduction of the electrical consumption of the furnace through electrical heating, as the heating elements will require less electricity for reaching 550°C. This allows the reduction on the energy consumption of the process making more environmentally friendly than before. Furthermore, the heated gases could improve the pyrolysis process itself by having a two-step heating (one form gases and second at pyrolysis temperature), however, this will be performed next. Energy simulation results from IRT Jules Verne provide an estimation of the innovative line efficiency. The modified gas flow architecture enables effective reuse of high-temperature gases, significantly improving the internal energy efficiency of the system with a 40% reduction in direct energy consumption.


CO_2
LCA

6

LIFE-CYCLE ASSESSMENT.

Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental impact of materials like bio-based resins, natural fibers, and recycled fibers. This article demonstrates how these sustainable alternatives compare to traditional materials, focusing on their energy-efficient processing and real-world applications. By analysing their life cycles—from raw material extraction to end-of-life—we uncover opportunities to reduce carbon footprints by identifying hotspots. The low maturity of the materials that we have developed is making the comparison difficult with legacy industrialised products and further research and development is necessary to obtain the full picture.

LCA of SUSPENS materials

Context & technical challenges

The Life Cycle Assessment (LCA) conducted within the SUSPENS project faced several methodological and data-related challenges, which are typical when assessing emerging sustainable composite systems.

A key limitation was the lack of representative and high-quality life cycle inventory (LCI) data for some of the materials and processes investigated within the scope of this project. Since these materials and processes are still under development or not yet widely industrialized, they are often not included in standard LCA databases such as Ecoinvent.

To address these gaps, proxy datasets were used, complemented by data from scientific literature. While this approach enables the assessment to proceed, it introduces uncertainty and requires careful selection of analog processes and sensitivity analyses to ensure robustness of the results.

Additionally, assumptions had to be made regarding scaling from laboratory or pilot-scale production to industrial-scale manufacturing, which can significantly influence environmental performance.

Development objectives

SUSPENS sustainability target:

The project aims to demonstrate that the use of bio-sourced and recycled materials, combined with optimized composite manufacturing and innovative recycling processes, can lead to CO_2 emission reductions of more than 40% across the whole composite life cycle.

Specific KPIs:

- Lignin-based CFs: ~60% reduction in CO_2 emissions compared to PAN-based carbon fibers.
- Recycled GF: ~12–18% reduction in energy demand and CO_2 emissions compared to virgin glass fibers.
- Recycled CF: Energy demand reduced to ~10% of that required for virgin carbon fiber production.

These targets are intended to demonstrate the environmental advantages of alternative materials and processes, while ensuring their suitability for industrial applications. By validating these improvements, SUSPENS supports the transition towards low-carbon composite value chains.

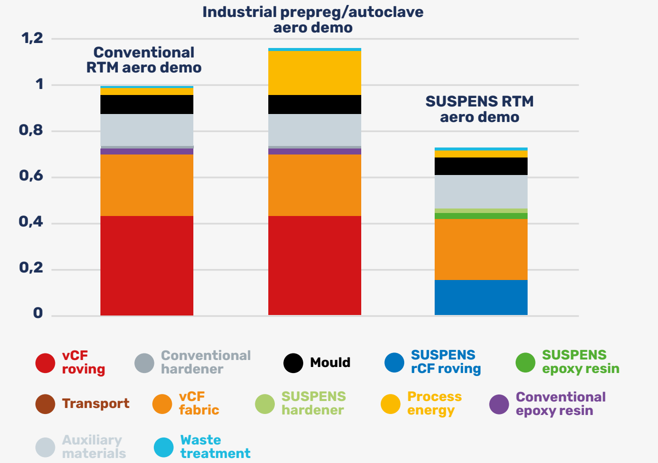
Approach & methodology

Life Cycle Assessment (LCA) is an internationally standardized methodology defined by ISO 14040:2006 and ISO 14044:2006 for quantifying the environmental impacts associated with the full life cycle of a product, process, or service. ISO 14040 defines the general principles and framework, while ISO 14044 specifies the methodological requirements and guidance. In this project, a cradle-to-gate LCA was performed, covering raw material extraction, SUSPENS material production, and composite manufacturing. Dedicated system boundaries were defined for the end-of-life assessment to evaluate the solvolysis and pyrolysis recycling technologies developed within SUSPENS and applied to representative GFRP and CFRP composite systems. All materials and processes were modelled using SimaPro v10.3.0.1 with the Ecoinvent v3.10 database. The Environmental Footprint 3.1 (EF 3.1) methodology, developed by the European Commission Joint Research Centre, was applied for life cycle impact assessment.

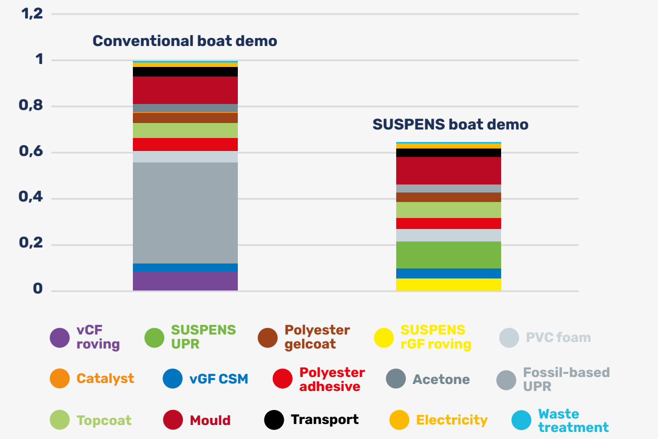
Key findings

Normalized contribution of processes and materials to climate change impact relative to the reference scenario

Aerospace

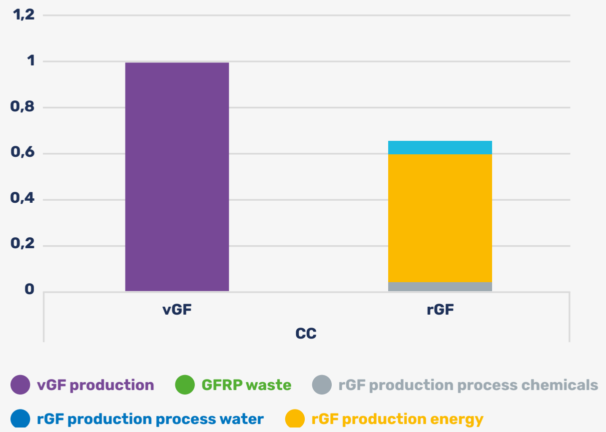


Sailing boat



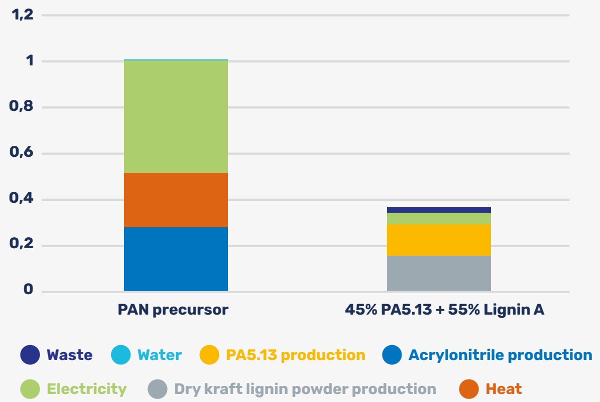
Recycled glass fiber (rGF)

Climate change impacts are reduced by 35% compared to virgin glass fiber, mainly due to the avoidance of energy-intensive primary melting processes.



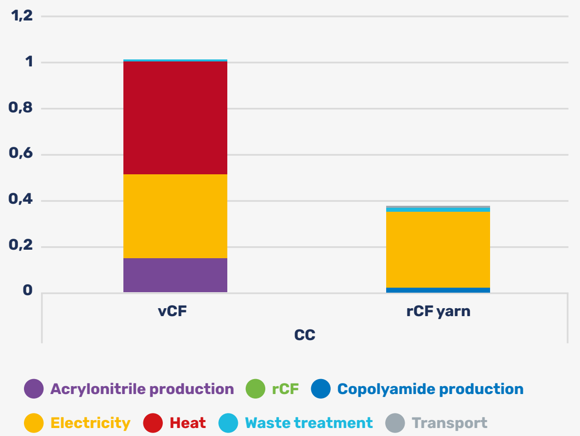
Lignin-based carbon fiber precursor

Climate change impacts are reduced by 63% compared to the PAN-based precursor, mainly due to the use of low-impact lignin and biopolymer feedstocks, avoiding energy-intensive petrochemical acrylonitrile production and solvent-based processing.



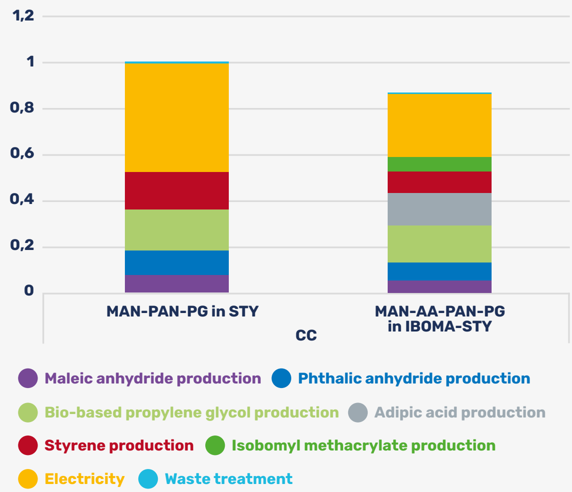
Recycled carbon fiber (rCF) yarn

Climate change impacts are reduced by 62% compared to virgin carbon fiber, primarily because the most energy-intensive steps—stabilisation and carbonisation—are avoided.



Bio-based UPR *(MAN-AA-PAN-PG in IBOMA/STY 1:1)*

Climate change impacts are reduced by 12% compared to the reference resin (MAN-PAN-PG in STY), mainly due to reduced electricity demand during production.



Impact & added value

The results demonstrate that the use of bio-based and recycled materials can significantly improve the environmental performance of composites. The integration of these materials with optimized manufacturing and recycling routes supports more sustainable and circular production systems. Overall, the achieved impact reductions demonstrate the added value of SUSPENS solutions in advancing low-carbon composite materials.

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TES
Developing bio-based
and recyclable composites

7 HIGHLIGHTS.

Dissemination activities played an important role in raising awareness of the SUSPENS project and its results. Through events, publications, online communication, and networking opportunities, the consortium shared key achievements, exchanged knowledge with relevant stakeholders, and helped promote the uptake of the SUSPENS project outcomes. These activities contributed to extending the project's reach and ensuring that its results can continue to generate benefits beyond the end of the project.

7.1 Events

SUSPENS at **JEC World 2026**

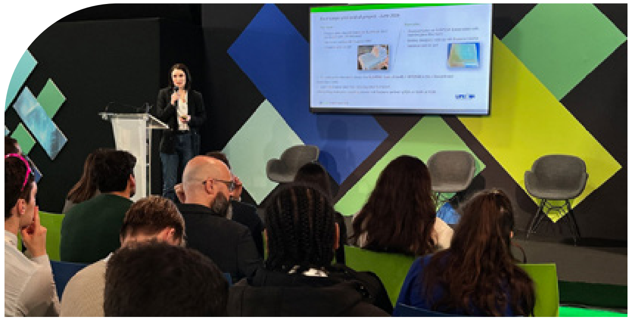
A major dissemination achievement for SUSPENS was its participation in the 2026 edition of the JEC World 2026, one of the world's leading international events dedicated to composite materials.

The project was showcased at the EcoComposites Cluster stand, providing high visibility among industrial stakeholders, researchers, policymakers, and innovation actors from across the composites value chain. The event offered an excellent opportunity to disseminate project results, engage with potential end users, and strengthen collaboration with other European initiatives working towards sustainable composites.

SUSPENS also contributed to the conference programme through two technical presentations:

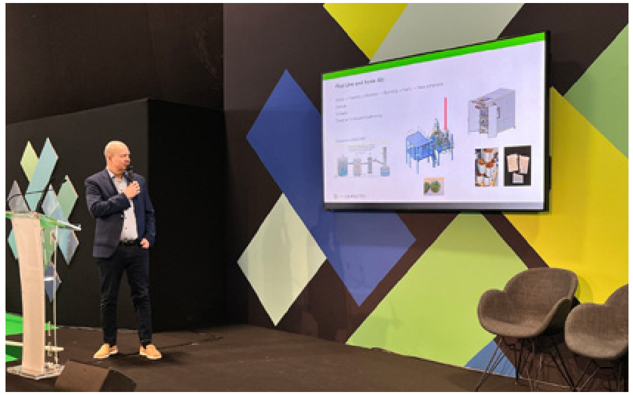
- Lightweight and Sustainable Composite Parts for Transport Applications – *Justine Martin (COMPOSITEC)*
- Recycling and Circularity Strategies for Next-Generation Composite Materials – *Tapio Korhonen (LIPEX)*

JEC WORLD 2026 The Leading International Composites Show
March 10-12 PARIS-NORD VILLEPINTE



To further encourage stakeholder engagement, the EcoComposites Cluster organised a networking cocktail reception at its exhibition stand. The event brought together European Commission Project Officers, policy experts, industry representatives, and research organisations, creating a valuable forum for discussing project achievements, future exploitation opportunities, and the challenges associated with the transition towards sustainable composite materials.

Participation in JEC World 2026 significantly enhanced the visibility of SUSPENS, facilitated the dissemination of project results to a broad international audience, and reinforced cooperation within the European composites community.



EcoComposites Cluster: Advancing bio-based and recyclable composites

ECOCOMPOSITES

SUSPENS is part of the EcoComposites Cluster, which brings together six Horizon Europe projects committed to accelerating the transition towards more sustainable composite materials. Through the development of bio-based alternatives, innovative recycling technologies, and circular design approaches, the Cluster promotes collaboration and knowledge exchange across the European composites ecosystem.

r-LightBioCom · repoxyble · furhy · MC4 · FOREST

SUSPENS at **ECCM22**

Another key dissemination milestone is the participation of SUSPENS in the ECCM22, held in Norway in June 2026.

In collaboration with the sister projects FOREST and R-LightBioCom within the EcoComposites Cluster, SUSPENS co-organised a dedicated thematic session entitled "EcoComposites Cluster – Sustainability of Composites in the Transportation Sector." This session served as a platform to showcase the latest scientific and technological developments achieved by the participating projects and to engage with the wider composites research and industrial community. The session featured seven contributions from SUSPENS consortium partners, highlighting key project results related to sustainable materials development, lightweight design, circularity strategies, and recycling solutions for transportation applications.

ECCM22
22nd EUROPEAN CONFERENCE ON COMPOSITE MATERIALS

Broad scientific outreach through international conferences and fairs

Beyond its participation in major cluster-driven events, SUSPENS actively disseminated its results through numerous international scientific and industrial conferences throughout the project duration. Consortium partners presented research findings, technological developments, and demonstration results at leading events dedicated to composite materials, sustainable manufacturing, circular economy, and transport applications.

ICCM 23 INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS BELFAST 2023 30 JULY – 4 AUGUST

ECCM21 02-05 July 2024 Nantes - France

EUROPEAN COATINGS SHOW 2023

JEC WORLD 2025 The Leading International Composites Show

54e SALON INTERNATIONAL DE L'AÉRONAUTIQUE & DE L'ESPACE PARIS · LE BOURGET 19-25, JUIN 2023

7.2 Scientific publications

Investigation of Carbon Fibres Reclamation by Pyrolysis Process for Their Reuse Potential

Authors: Stefania Termine, Valentina Naxaki, Dionisis Semitekolos, Aikaterini-Flora Trompeta, Massimo Rovere, Alberto Tagliaferro, Costas Charitidis

Abstract

During Carbon Fibre Reinforced Polymers (CFRPs) manufacturing, large quantities of scrap are being produced and usually disposed to landfill or incinerated, resulting in a high environmental impact. Furthermore, CFRP parts that have been damaged or reached their end-of-life, follow the same disposal route and because of this, not only the environment is affected, but also high added-value materials, such as carbon fibres (CFs) are lost without further valorisation. Several recycling technologies have been suggested, such as pyrolysis, to retrieve the CF reinforcement from the CFRPs. However, pyrolysis produces CFs that have residual resin and pyrolytic carbon at their surface. In order to retrieve clean long fibres, oxidation treatment in high temperatures is required. The oxidation treatment, however, has a high impact on the mechanical properties of the reclaimed CFs; therefore, an optimised pyrolysis procedure of CFRPs and post-pyrolysis treatment of reclaimed fibres (rCFs) is required. In this study, CFRPs have been subjected to pyrolysis to investigate the reclamation of CF fabrics in their primal form. The temperature of 550 °C was selected as the optimum processing temperature for the investigated composites. A parametric study on the post-pyrolysis treatment was performed in order to remove the residues from the fabrics and at the same time to investigate the CFs reusability, in terms of their mechanical and surface properties.

https://www.mdpi.com/2073-4360/15/3/768

Recent Trends of Recycling and Upcycling of Polymers and Composites: A Comprehensive Review

Authors Christina Podara, Stefania Termine, Maria Modestou, Dionisis Semitekolos, Christos Tsirogiannis, Melpo Karamitrou, Aikaterini-Flora Trompeta, Tatjana Kosanovic Milickovic, Costas Charitidis

Abstract

This review article gathers the most recent recycling technologies for thermoset and thermoplastic polymers. Results about existing experimental procedures and their effectiveness are presented. For thermoset polymers, the review focuses mainly on fibre-reinforced polymer composites, with an emphasis on epoxy-based systems and carbon/glass fibres as reinforcement, due to the environmental concerns of their end-of-life management. Thermal processes (fluidised bed, pyrolysis) and chemical processes (different types of solvolysis) are discussed. The most recent combined processes (microwave, steam, and ultrasonic assisted techniques) and extraordinary recycling attempts (electrochemical, biological, and with ionic liquids) are analysed. Mechanical recycling that leads to the downgrading of materials is excluded. Insights are also given for the upcycling methodologies that have been implemented until now for the reuse of fibres. As for thermoplastic polymers, the most state-of-the-art recycling approach for the most common polymer matrices is presented, together with the appropriate additivation for matrix upcycling. Mechanical, chemical, and enzymatic recycling processes are described, among others. The use of fibre-reinforced thermoplastic composites is quite new, and thus, the most recent achievements are presented. With all of the above information, this extensive review can serve as a guide for educational purposes, targeting students and technicians in polymers recycling.

https://www.mdpi.com/2313-4321/9/3/37

Low-Viscosity Eutectic Hardeners for More Sustainable Cross-Linking Conditions

Authors: Mona Jamali-Moghadam-Siahkali, Nathanael Guigo, Luc Vincent, Nicolas Sbirrazzuoli

ACS Publications
Most Trusted. Most Cited. Most Read.

Abstract

Preparation of very-low-viscosity eutectic mixtures was proposed for incorporating high-melting-temperature citric acid (CA) as a reactive cross-linker for curing of thermoset resins. By preparing the 1:1 molar ratio of CA with either diethyl malonate (DEM), diethyl succinate (DES), diethyl glutarate (DEG), diethyl oxalate (DEO), or triethyl citrate (TEC), the citric acid melting temperature (153 °C) decreased under −50 °C, which is more than 200 °C lower than the pure CA melting temperature. Furthermore, a significant depression in the mixture viscosity to few pascals (1.5 to 5.3 Pa•s) was observed for CADEG, CDAES, CADEM, and CADEO leading to optimal mixing with the resin. The eutectic mixtures were then used to cure the epoxidized linseed oil (ELO) in two steps. The highest glass transition of 40 ± 1 °C was obtained for CADEM-ELO, followed by a significantly higher Young's modulus of 101 ± 7 MPa, a tensile strength of 45 ± 3.7, and a stress at break of 10 ± 0.7 compared to other thermosets using EHs. Considering the thermal and mechanical properties, the superior performance of CADEM-ELO over other systems was confirmed by its lowest swelling ratio (78 ± 10) and highest gel fraction (93 ± 2).

https://pubs.acs.org/doi/10.1021/acsapm.4c00510

Catalytic Effect of Eutectic Hardeners to Polymerize Epoxidized Vegetable Oil for the Synthesis of Fully Biobased Thermosets at Low Temperatures

Authors: Mona Jamali Moghadam Siahkali, Nathanael Guigo, Luc Vincent, Nicolas Sbirrazzuoli

ACS Publications
Most Trusted. Most Cited. Most Read.

Abstract

Four different eutectic hardeners (EH) were used to polymerize epoxidized linseed oil. The study highlights very different rate-limiting steps for systems with and without EHs resulting in different final properties. The reaction starts at a much lower temperature in the presence of EH (around 50–80 °C lower), and one system (CATEC-ELO) starts to react at a temperature around 30–40 °C below that of the other EH systems. The different reactivities and final properties of this system are explained by the presence of a hydroxyl group, a more hindered structure, and hydrogen interactions. The reactivity of CATEC-ELO can be parametrized with a two-step competing mechanism (TSC), while the other systems are described by an autocatalytic step, followed by diffusion control of short polymer chains. The four methods proposed in this study, TSC, SVM, VSD(n), and SD(n,p), enable a very good modeling of the polymerization rate. The method of SVM is quite fast and gives very accurate results. The methods SVM, VSD(n), and SD(n,p) combine an autocatalytic step and a term that accounts for diffusion. A new method (SD(n,p)) is presented in this study. It appears that the procedure proposed using several steps yields meaningful kinetic parameters, even in the more complex case where 10 parameters are determined (SD(n,p) method).

https://pubs.acs.org/doi/full/10.1021/acs.macromol.4c02107

Low-viscosity, highly processable biobased thermoset polymers from phloroglucinol Tris-epoxy resin with a green eutectic hardener

Authors: Mona Jamali Moghadam Siahkali, Nathanael Guigo, Luc Vincent, Nicolas Sbirrazzuoli

ScienceDirect

Abstract

This study presents the development of sustainable biobased thermosets, meeting high performance polymer properties. Two formulations were prepared through curing phloroglucinol tris epoxy resin (PHTE) with two bio-based eutectic hardeners (EH) synthesized from citric acid (CA) and diethyl malonate (DEM) at stoichiometric ratio of 0.5 and 1 $\left(R_{\text{eutectic}}\left(\frac{n\ (DEM)}{n\ (CA)}\right) = 0.5{,}1\right)$. These formulations present advantages such as, high biobased content, low viscosity of few Pa.s and efficient thermal and mechanical properties. The glass transition temperatures ranging from 83 °C to 114 °C, Young's modulus of ≈ 2.8 GPa and a thermal stability (T10%) above 300 °C were obtained for the two biobased thermosets. Using eutectic hardeners to formulate high performance PHTE based thermosets has the potential to reduce the curing temperature, lowering the viscosity leading to easy processability contributing to increase the polymeric mixture homogeneity in high performance material manufacturing processes.

https://www.sciencedirect.com/science/article/pii/S1381514826001264?via%3Dihub


January 2023 - France (Nantes) - IRT Jules Verne


June 2023 - Belgium (Ghent) - Centexbel


January 2024 - France (St-Malo) - COMPOSITEC


June 2024 - Finland (Espoo) - AALTO

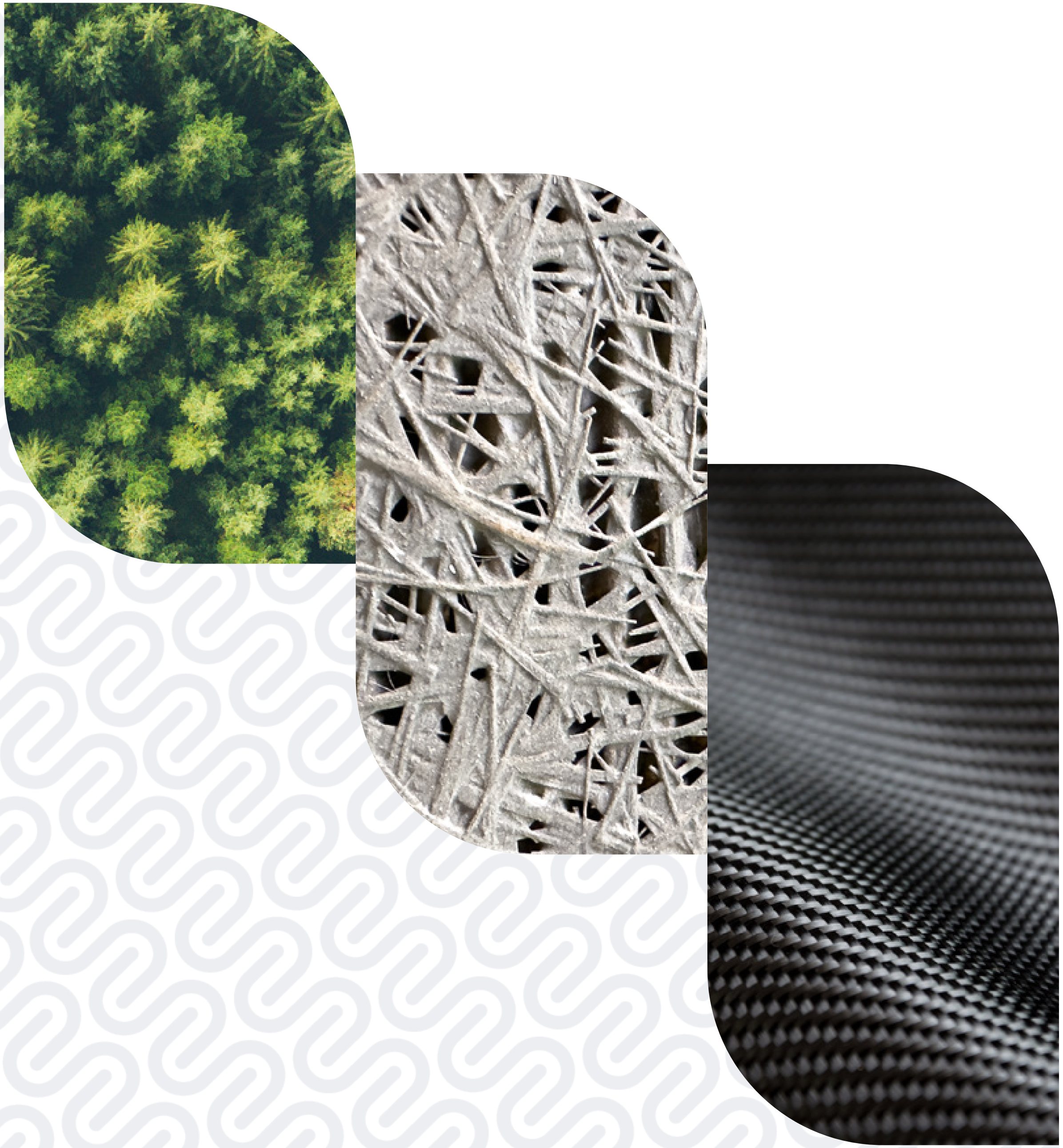

January 2025 - France (Nice) - UCA


June 2025 - Portugal (Lagos) - APM

January 2026 - Greece (Athens) - NTUA

SUSPENS General assemblies.


June 2026 - France (Nantes) - IRT Jules Verne



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