Global Trends in Aerospace Green Composite Materials

绿色航空复合材料技术及其国际化发展

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长三角碳纤维及复合材料创新中心

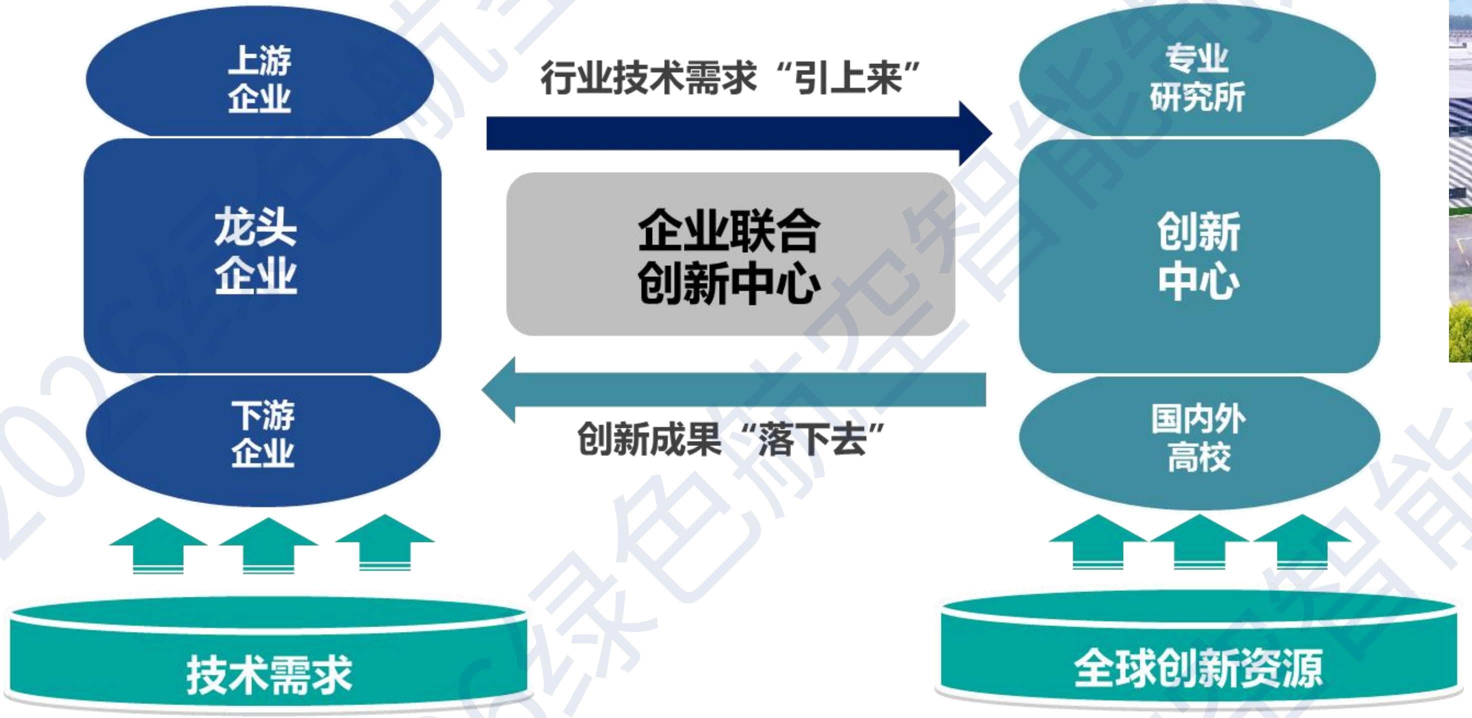
CCIC, A National Innovation Center
长三角碳纤维及复合材料创新中心

NICE CCIC 长三角碳纤维及复合材料技术创新中心

Mission: to grow the regional composites industry by

- Technology transfer from lab to factory
- Nurturing startups and spin outs
- Promoting education and training
- Raising public awareness of composites

Established 2022
with regional funding



Key Activities

- Laboratory access for applied research and technology scale-ups
- Research partnerships
- Technical consultancy
- Commercialization
- Education and training
- Public awareness

80,000m² for R&D labs and scale-up facilities

重大项目平台	
产业聚焦	**关键技术**
1. 航空航天	1. 先进碳纤维
2. 土木工程与大型结构	2. 高性能多功能复合材料
3. 双碳与可持续发展	3. 异质材料连接
4. 关键装备	4. 装备轻量化
5. 清洁能源	5. 全寿命周期与可循环应用

公共服务平台
1. 检测评价
2. 中试研制
3. 成型制造
4. 技能培训
5. 平台开拓（网络）

目标：建设良性循环平台，实现创新性可持续发展

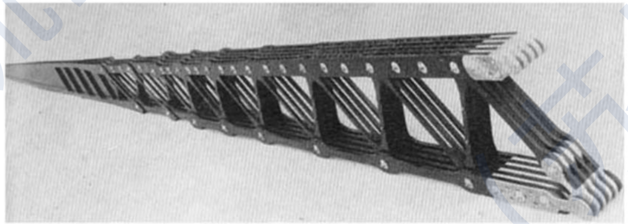
Green composites have been around for a long time

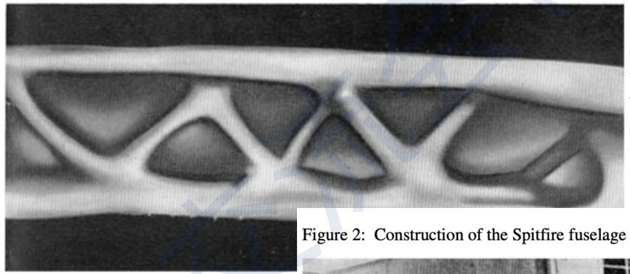
绿色复合材料并非新生事物

- Has progress in implementation matched our rate of technology advance?
- What is the level of impact on our industry and its reliance on petroleum?
- How can we make a better case for green composites
- 绿色复合材料技术实际应用的进展是否与技术演进速率相匹配?
- 其对产业转型及降低石油依赖度的影响程度如何?
- 如何为推广绿色复合材料应用提供更具说服力的依据?

The history of advanced composites is also the history of green composites!
先进复合材料的发展史，亦是绿色复合材料的演进史

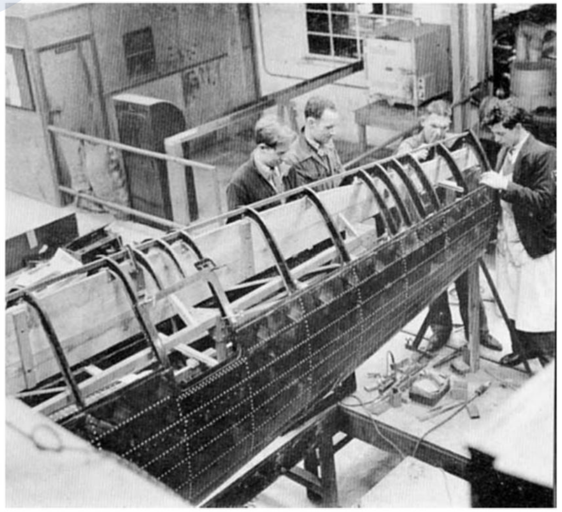
- Flax-Phenolic aerostructures were fabricated in Europe from 1939-41 due to war-time aluminium shortages
- 2 x specific stiffness of glass fibres/Identical weight to Al alloy fuselage
- Pioneering work by Dr N.A DeBruyne, also first to create bonded aerostructures





Bishopp J.. In:. Sealar
vol. 1, Elsevier Scienc
Ltd; 2005

Figure 2: Construction of the Spitfire fuselage using Gordon Aerolite [13].



- **战时需求催生应用**：1939–1941年间，因战时铝材短缺，欧洲首次采用亚麻-酚醛（Flax-Phenolic）制造航空结构件
- **优异的物理性能**：**比刚度**达到玻璃纤维的**2倍**；**整体减重**与传统铝合金机身**完全等重**
- **行业先驱**：由 **N.A. DeBruyne 博士**开展的开拓性工作，他也是全球首位实现**胶接航空结构**的科学家

使用亚麻/酚醛复合材料建造英国Spitfire战斗机机身

Aerospace Composites: Market & Drivers
航空复材：市场规模与核心驱动力

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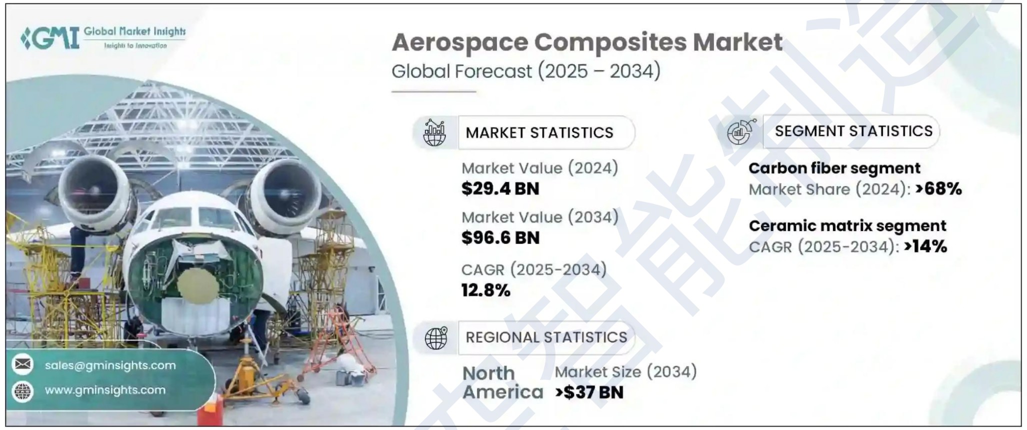

Market Landscape 全球市场格局

■ Market Scale & Hyper-Growth 市场总量爆发式增长

Market value surge: **$29.4 BN** (2024) ➔ **$96.6 BN** (2034) at a **CAGR of 12.8%** *(Note: Civil Aero growing c.8%, 2021-26, JEC)*

2024年 **294亿美元** ➔ 2034年预测 **966亿美元**，复合年增长率 **12.8%** *（其中民用航空板块年增长率约 8%，2021-26, JEC数据）*

■ Segment Status & Material Forms 细分市场与材料形态

CFRP dominates with **>68%** market share; **75%** of material volume (~36 kT) is processed as **prepreg**

碳纤维复材占据绝对主导（份额 **>68%**），**75%** 为**预浸料**形态

■ Geographic Concentration 地缘格局

North America exceeds **$37 BN** by 2034; USA alone accounts for around **40%** of glob...

北美市场空间最大（2 ...
40% 的物料

Performance & Benefits 全寿命周期效益

The Weight-to-Fuel Leverage 核心减重与节油杠杆

Core physical rule: **1% drop** in aircraft weight leads to a **0.75% reduction** in fuel use (Structural weight accounts for c.55% of operating empty weight (OEW) and ~27% of max take-off weight (MTOW) (Horst & Wolf, 2014))

飞机**结构减重1%**，可直接降低**0.75%的燃油消耗** （结构重量约占飞机OEW的55%以及MTOW的27%）

■ Engineering Mass Reduction Gains 结构减重空间

Mass reduction of **20%** compared to traditional Al structures (e.g., Boeing 787 Dreamliner)

Largest gains (SHAC) are achieved in the wing (27%) and fuselage (14%) (Helleman et al., 2025). Cabin interiors, seating, and even paint systems can contribute further.

相比传统铝合金结构，整体实现 **20% 的大幅减重**（以波音 787 客机为例）

最大减重效益集中于机翼（27%）与机身（14%）,客舱内饰、座椅乃至涂装系统可作进一步的减重贡献。

■ Economic & Environmental Balance 经济与环境效益权衡

In-Service Gains 服役期综合效益

Climate change impact reduced by **c.30%**; total cost savings of **$15.88 million** can be achieved over the aircraft's service life.

气候影响降低约**30%**；在飞机整个服役寿命周期内，单机可实现节省**1588万美元**运营成本

Initial Cost Challenge 初期成本惩罚

...).

To what extent are in-service benefits offset by energy intensive CFRP production?
飞机服役期的减碳效益，是否正被高能耗的碳纤维制造过程所透支？

Greening the Aerospace Supply Chain: Three Core Pillars
航空航天供应链绿色化：三大核心支柱

1. Fibre Reinforcements 纤维增强体

■ Evaluation & Analytical Dimensions 核心评估与分析

Markets and growth 市场与增长趋势：聚焦全球航空供应链的规模演进与未来增长空间

Environmental footprint 环境足迹评估：严苛穿透材料制造到服役全生命周期的碳排与生态影响

Data quality 数据质量与可靠性：确保底层数据库的真实性，防止出现绿色航空领域的“绿色欺诈（Greenwashing）”

■ Material Classification & Key Variables 材料分类与控制变量

Synthetic Fibres 合成纤维(如传统碳纤维、高性能玻璃纤维)

- Precursors 前驱体原料：前驱体材质与化学合成路径
- Energy Sources 能源结构与来源：碳纤维生产中的电力与热能构成
- Yields 产率：降低从前驱体到成品纤维的损耗
- Processing 工艺制造加工：高能耗阶段的绿色低碳工艺改良
- LCA data 生命周期评价数据：高能耗制造数据量化

Opportunity Bandwidths	Estimated Energy Savings Opportunity for CFRP Composite Manufacturing (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	1.21 TBtu[5] (22.1% energy savings)[6]
R&D Opportunity – additional energy savings if applied R&D technologies under development worldwide are successfully deployed	3.43 TBtu[7] (62.6% energy savings)[8]

US DoE bandwidth study 2017

Natural Fibres 天然纤维（如航空级亚麻、大麻纤维)

- Sourcing 原料采购与溯源：产地分布、供应链合规与稳定度
- Cultivation 农艺种植与培育：土地占用、碳汇贡献与农业投入品
- By-products 副产物综合利用：全株利用，构建经济闭环
- Processing ：机械与化学加工工艺：脱胶、梳理与表面改性减排
- LCA data 生命周期评价数据：量化评估全生命周期的净负碳能力

Textiletrainer.com

Concreteconstruction.com

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2. Bio-Resins & Sustainable Matrix Systems 生物基树脂

■ Evaluation & Analytical Dimensions 核心评估与分析

Biomass Content & Transparency 生物质含量与透明度：严格量化可再生生物质成分的真实比例

Standards & Certification 标准体系与适航认证：推动树脂体系对接国际材料标准，确保航空级全流程可追溯性

LCA Data & Footprint LCA数据与环境足迹：追踪从化学合成到最终废弃处置全生命周期的减碳表现

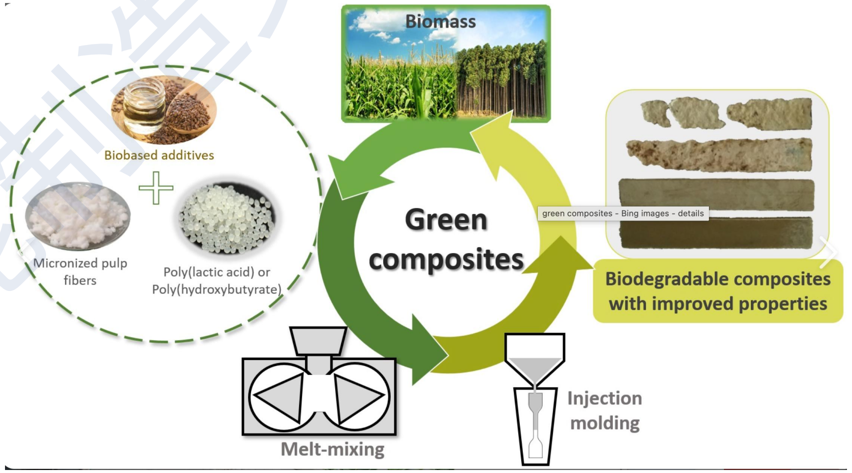
The Bio-Resin Landscape 绿色树脂的市场格局与分类

- **Mainstream Families 主流生物基树脂谱系**

PLA (95%+ bio-content from corn/starch), Bio-PE/PET(sugarcane-derived), and Bio-Polyamides (castor oil)

PLA（源自玉米/淀粉，生物基含量 95%+）、生物基 PE/PET（甘蔗提取）及生物基聚酰胺（蓖麻油提取）

	Source	Bio-content	Examples
PLA	Fermented cassava, corn starch etc	95%+	Natureworks Inego®
Bio-Polyethylene	Sugarcane ethanol	90%+	Braskem I’ m Green®
Bio-PET	Sugarcane Ethylene Glycol	20%+	Teijing Eco-circle® PET fiber (30%)
Polyhydroxyalkanoates (Polyesters)	Fermented sugars, vegetable oils	100%	Tianan Enmat® PHBV
Bio-Polyamides	Castor Oil	60%-100%	Arkema Rilsan® PA11
Lignin, Soy based Epoxies	Wood pulp, Epoxidized Soybean oil	30%+	Sicomin Greenpoxy® 51%, Entropy Supersap® 37%
Methacrylate (monomers)	Bioethanol	<85%	Evonik Terra IBOMA®
Bio-PUs (foams, coatings)	Bio-polyols from soy, castor, or palm	20%+	Huntsman Ibond(25%), Lubrizol Estane® (30%)
Cellulose Acetates	Wood pulp cellulose	40%+	Eastmann CA (41%), Daicell CA
Natural Rubbers	Latex	100%	Ubiquitous



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The Bio-Resin Landscape 绿色树脂的市场格局与分类

- **Current Application Bottleneck 现有应用市场的局限性**

Current market remains heavily skewed toward Packaging, Consumer Goods, and Automotive (Packaging > Consumer Goods > Automotive).

当前应用市场仍严重向包装、消费品、汽车领域倾斜，尚未大规模渗透进高壁垒的航空主承力结构

- **The High-Value Focus 高价值核心焦点**

Note: Bio-Epoxy occupies the smallest volume but holds the highest technological value.

生物基环氧树脂目前出货量最小，但占据了最高的行业技术价值。

Avoiding "Greenwashing" via Regulatory Standards
引入权威标准，杜绝“绿色欺诈”

Summary Table

Standard	Measures	Method Type	Region
ASTM D6866	Bio-based carbon content	Radiocarbon (C-14)	US / Global
EN 16785-1	Total bio-based content	Mass balance + analytical	EU
ISO 16620-2	Bio-based carbon content	Radiocarbon	Global
ISO 16620-3	Total bio-based content	Mass balance	Global
CEN/TS 16137	Bio-based carbon	C-14	EU

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航空航天供应链绿色化：三大核心支柱


Dreamstime.com

2. Bio-Resins & Sustainable Matrix Systems 生物基树脂

■ **Economic Penalties & The Aviation FST Wall 经济可行性与航空 FST 适航应用挑战**

● **The “Elephant in the Room” - Economic Realities 经济可行性与成本制约**

Immature Industrial Chain 产业链不够成熟：Higher synthesis cost due to fragmented supply chains, immature supply base, and low bioprocessing throughput compared to petrochemical cracking.

相比传统石油化工催化裂解，生物制造由于供应链分散、供应基地不成熟、工艺得率低，导致化学合成成本先天偏高。

The Upfront Cost Penalty 触目惊心的初期成本：High-performance Bio-Epoxy carries a staggering 200%+ cost penalty compared to standard fossil-derived epoxy benchmarks.

与传统石化环氧树脂基准相比，高性能生物基环氧树脂的初期原材料成本惩罚高达 200%+。

● **The Aviation Technical Barrier 航空技术与安全壁垒**

The Fire, Smoke & Toxicity (FST) Wall 阻燃、低烟、低毒要求：Standard bio-polymers collapse under high-temperature engine or cabin fire scenarios, disqualifying them from primary aeronautical use.

常见的生物基树脂（如 PLA、生物基 PET）在消费品领域应用广泛，但它们完全无法满足航空极严苛的耐热与防耐火安全要求。

The Strategic Matrix Choice 航空级绿色酚醛：Aerospace interiors and sub-structures demand advanced chemistry; Bio-Phenolics represent the primary viable pathway to satisfy strict aerospace FST mandates.

航空内饰与次承力结构要求极高；**生物基/绿色酚醛树脂**是目前满足航空严苛 FST 适航法规的最核心可行技术路径。

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3. Sustainable Ancillary Materials & Processing Optimisation 绿色工艺辅助材料与加工工艺优化

■ Process Characteristics & Environmental Challenges 工艺特征与环境制约要素

Aerospace Manufacturing Baseline 航空制造基准工艺： Large aircraft structural components are typically fabricated via conventional vacuum bagging or autoclave processes. 大型航空结构件通常依赖传统的真空袋辅助或热压罐工艺进行固化成型。

The Consumables Material Penalty 工艺辅材的固废处理制约： These processing methods require multiple types of single-use polymer films, fabrics, and felts—the vast majority of which are landfilled or incinerated post-manufacturing. 此类工艺需大量消耗多种一次性聚合物薄膜、织物和透气毡，制造完成后绝大部分只能采取填埋或焚烧方式处理。

Market Scale & Waste Volume Correlation 市场规模与固废总量正相关变动： The global aerospace composites market alone is forecast to reach USD 26 Billion by 2026, scaling up the total industry output of secondary processing waste. 仅航空航天复合材料这一细分市场规模预计到2026年就将达到260亿美元，这意味着全行业因加工产生的辅助固废总量也将同步放大。

■ Technical Optimization Vectors 绿色制造的核心技术优化

Advanced Processing Variables 先进成型制造: Transitioning toward Out-of-Autoclave (OOA) techniques, alternative heating methods, and net-shape manufacturing to directly reduce raw intensity and energy sources demand. 转向OOA成型技术、替代性加热及净零制造，从源头降低原材料初始消耗与能源需求。

Subsequent Finishing Technologies 后道加工与表面处理技术: Replacing petrochemical coatings with sustainable bio-based coatings, while leveraging non-traditional machining and laser/AWJ surface finishing. 采用可持续生物基涂层替代传统石化涂料，并综合应用非传统加工、激光及AWJ表面处理工艺。

Logistics & Supply Chain Clustering 物流效率与供应链集群化： Mitigating transport-related carbon footprints via strategic supplier clustering and integrated green transportation management. 通过战略性供应商集群化布局与绿色运输一体化管理，最大程度削减物流环节的隐性碳足迹。

CF Production, Energy and Emission Dilemma
碳纤维生产环节中能耗与排放的双重困境

- Energy consumption of **318.2 MJ/kg** and **CO_2 emission of about 20kg** for CF production.
  碳纤维（CF）生产能耗**318.2 MJ/kg**、**排放CO_2近20kg**。 (From Full LCA Report of Toray)
- CF manufacturing was found to be responsible for 59% of the climate change (CO_2 equivalent emission ranges from 13.0/kg - 34.1/kg) and 48% of the fossil resource use (from 262.3MJ/kg - 497.9MJ/kg). CF生产能耗对**气候影响高达59%**（CO_2气候影响当量从**13.0/kg - 34.1/kg**），对化石能源载体的消耗高达**48%**（资源使用范围从**262.3MJ/kg - 497.9 MJ/kg**）。(Source: Tobias Manuel Prenzel, Andrea Hohmann, Tim Prescher, Kerstin Angerer, Daniel Wehner, Robert Ilg, Tjark von Reden, Klaus Drechsler and Stefan Albrecht. Bringing Light into the Dark—Overview of Environmental Impacts of Carbon Fiber Production and Potential Levers for Reduction. ***Polymers*** 2024, 16, 12)

Waste from CF Products, Way out?
碳纤维复材废弃物：如何破局?

CF Demand and corresponding CFRP waste generation
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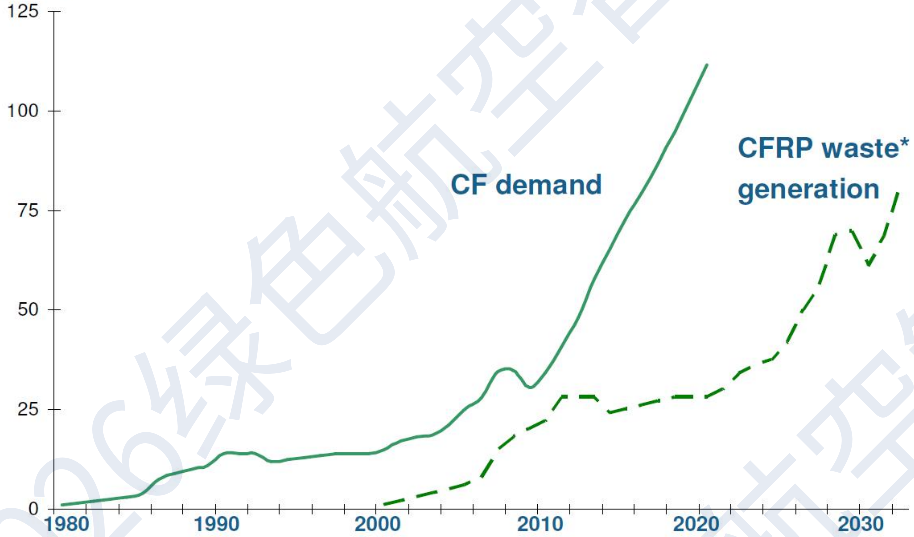
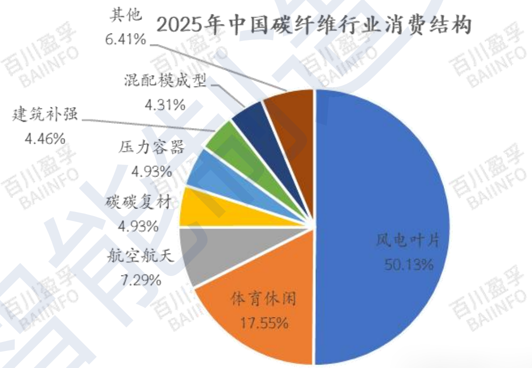
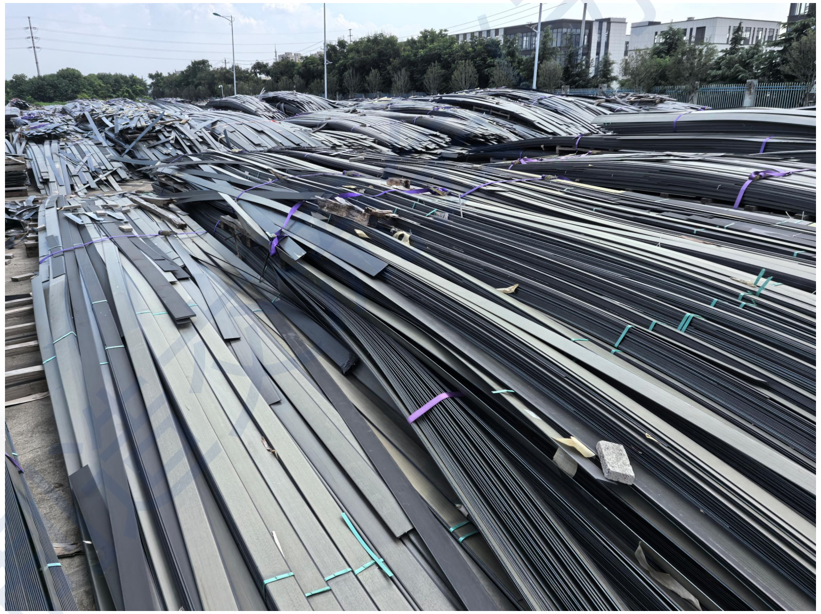


*assuming 1kg of CF generates 2 kg of CFRP waste at average CFRP-based product life time of 20 years
Source: SGL Group



Consumption proportion of China's CF industry



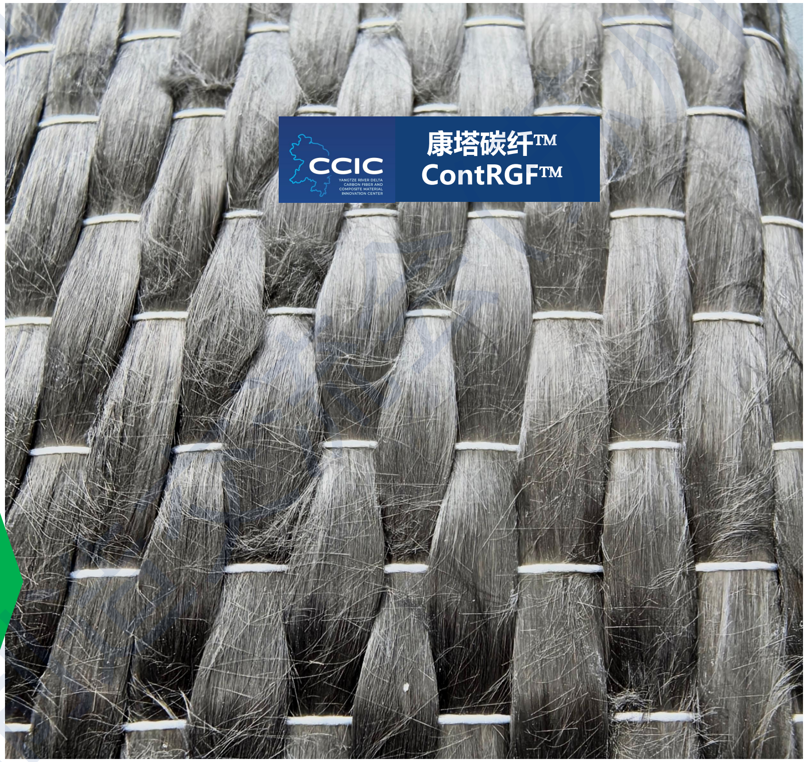
The path to breakthrough: all-green
全绿色复合材料

Raw material 原材料	Reinforcing fibers 增强纤维	Polymer matrix 树脂基体
Fossil-source 石化源（不可持续）	✗	✗
Bio-source 生物源（可持续）	✗	✓
Recycled 回收源（可循环）	✓	✗

ContRGF™ refers to a new continuous CF product made fully from recycled CF (rCF) rovings. The mechanical properties are in accordance with T/CSTM 00882-2023 "Industrial Grade Polyacrylonitrile-based Large Tow Carbon Fibre Yarn" group standard. It can be combined with bio-sourced resins to form cost-effective and all-green composites **ContRPMC™**.

Proprietary technology to remanufacture rCF

<u>**Proprietary Technology**</u> to remanufacture discontinuous rCFs to continuous bundles and furthermore rCF fabrics and cloths



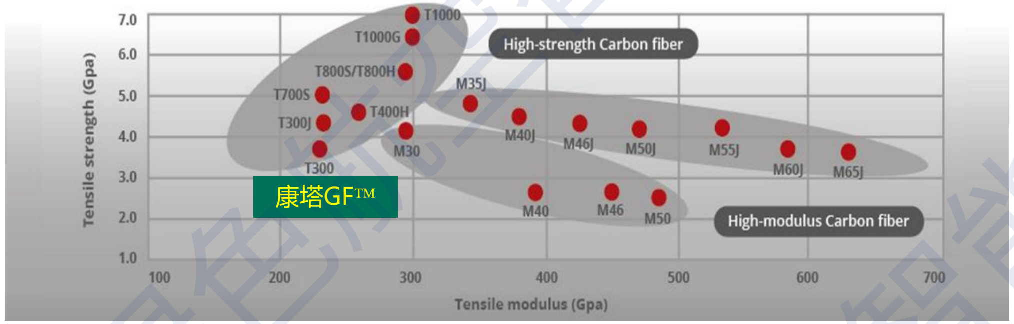
Example of trial products

康塔碳纤™的典型面密度（24k）/ Typical areal density of ContRGF™：200g/m² ~ 1000g/m²

ContRGF™ and ContRPMC™
自主研发全绿色复合材料

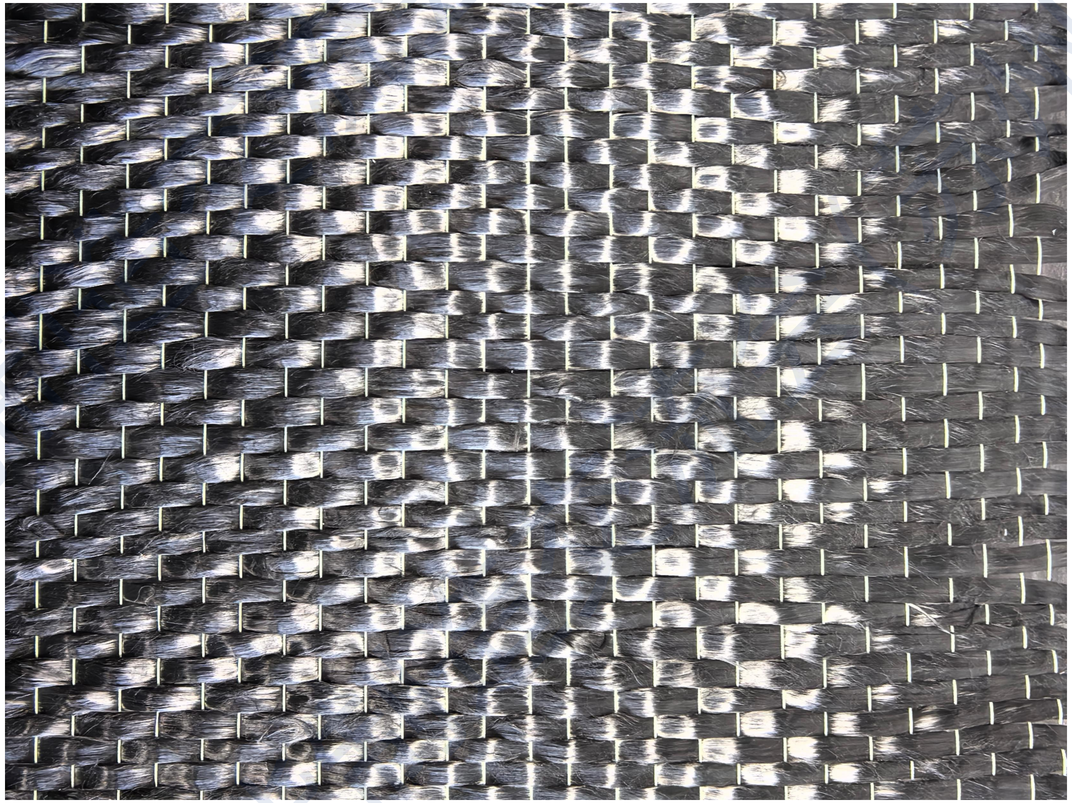
康塔碳纤™/ContRGF™（24k）

- 拉伸强度/tensile strength：2GPa~3GPa
- 拉伸模量/modulus：180GPa~300GPa
- 成本优势/cost：≤ ¥45元/kg



康塔绿材™/ContRPMC™（环氧/EP）

- 拉伸强度/tensile strength：~1.2GP, 60vol%CF
- 拉伸模量/modulus：~130GPa, 60vol%CF

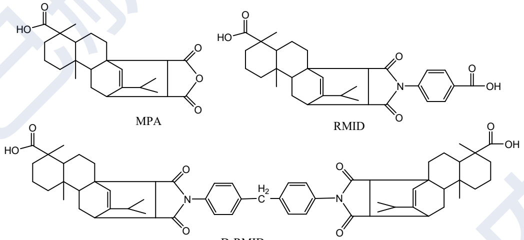


Bio-sourced resins and their CFRCs
生物基绿色树脂

8 EUROPEAN PARTNERS FROM 6 COUNTRIES

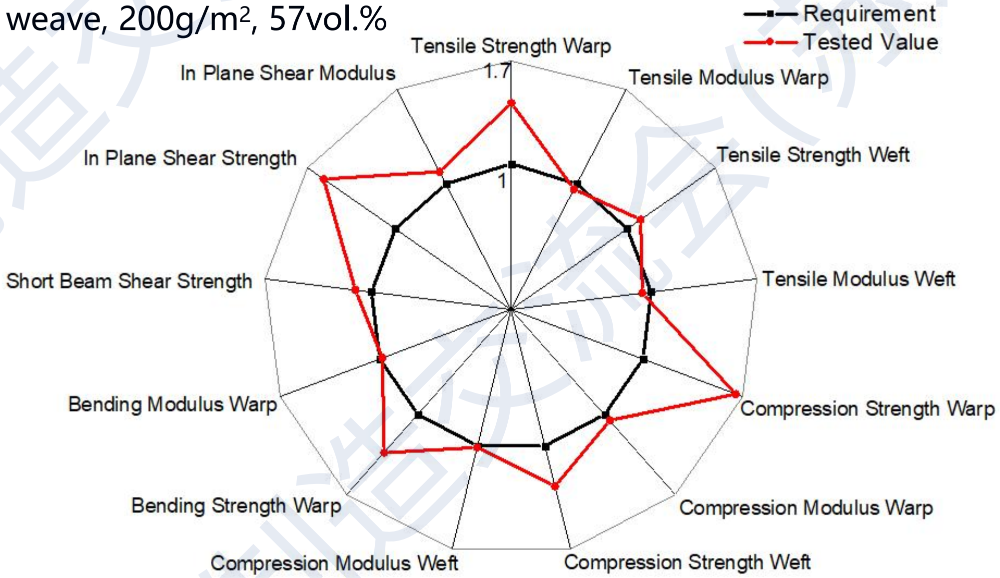
11 CHINESE PARTNERS

Rosin-EPs developed in ECO-COMPASS, a Sino-EU cooperation project.
中欧合作项目ECO-COMPASS开发的松香环氧树脂/碳纤维复合材料



Rosin-sourced epoxy hardener

CF plain weave, 200g/m², 57vol.%

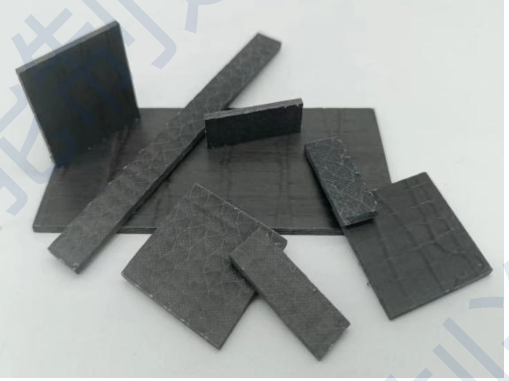


刘小青研究员团队

NICE CCIC 长三角碳纤维及复合材料技术创新中心

Recycling demonstration
全绿色复合材料的可控降解回收

康塔绿材™的RTM成型
RTMable bio-EP ContRPMC™



康塔绿材™试样在120°C/3~4hr条件下全降解过程
Controlled fully degradation of ContRPMC™ @120°C/3~4hr

康塔绿材™复合材料循环应用 /Circular economy of ContRPMC™

双酚A多元醇，环氧树脂和聚氨酯等的原材料
/Bisphenol A polyol, raw material for EPs and PURs

康塔绿材™复合材料中的碳纤维得以再次回收
CF recovered again from ContRPMC™

Green Resin: bio-based, formaldehyde-free araminolic resin

生物基绿色酚醛树脂

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Chinatiredealer.com

CCIC-Michelin Technical Synergy

Michelin First Flagship Project in China Non-Tire Composites Sector

米其林在中国非轮胎领域复合材料联合研发的首个落地项目

Focusing on the co-development of high-performance, sustainable, bio-based, and non-toxic resin systems, while validating their market potential across broader industrial use-cases.

联合攻克高性能、可持续、生物基无毒绿色树脂体系，并全面探索其在更广泛现代工业场景中的准入与应用潜力。

Eco-Breather Technology
绿色工艺辅材：生态透气毡：天然来源、一材多用

■ Global OEM Context of natural fibres 天然纤维工业界应用现状

● Current Application Boundaries 现有天然纤维的应用边界

Applications mainly limited to vehicle interiors – door cassette, seatback, parcel-shelf 欧洲主要整车 OEM已大量投入天然纤维结构研究，但其应用严格局限于非承力的汽车内饰件（如门板、椅背）

Instances will come and go along with legislative influences and public perceptions.具体应用实例（或研究热潮）往往伴随着法规政策的影响和公众舆论的认知而有起有落


Published 4/7/2022

BMW Group invests in Bcomp for high-performance natural fiber components

Collaborative partnership in motorsport moves to the next level for the use of renewable raw materials for future vehicle model components, and joint R&D materials work for production vehicles is underway.

SUSTAINABILITY AUTOMOTIVE MATERIALS NATURAL FIBERS REINFORCEMENTS

Edited by: GRACE NEHLS
Senior Managing Editor, CompositesWorld

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Figure 1.
Hemp fibers in vehicle doors [45].

Pecas P, Carvalho H, Leite M. 2018

Eco-Breather Technology
绿色工艺辅材：生态透气毡：绿色制造、循环经济

■ Green manufacturing: Eco-Breather 生态透气毡助力绿色制造

● The Polymer Softening Penalty 传统石化工艺辅材的高温失效惩罚

Breather felt is used to create a high permeability channel next to the vacuum membrane to expedite air removal and laminate consolidation.

Conventional breather felts rely on needlepunched virgin polymers like PET or PA6 (typically weighing around 300 g^2/m), which are completely discarded as solid waste after a single processing cycle.

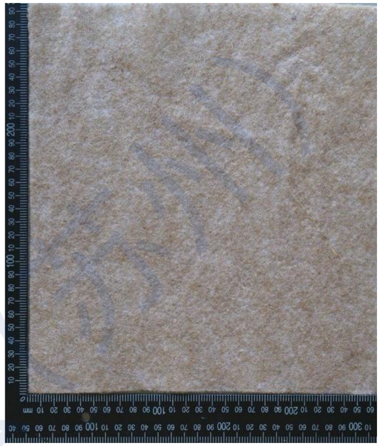
传统真空袋成型透气毡由 PET 或 PA6 制成，制造完成单次工艺周期后即作为固废完全丢弃。

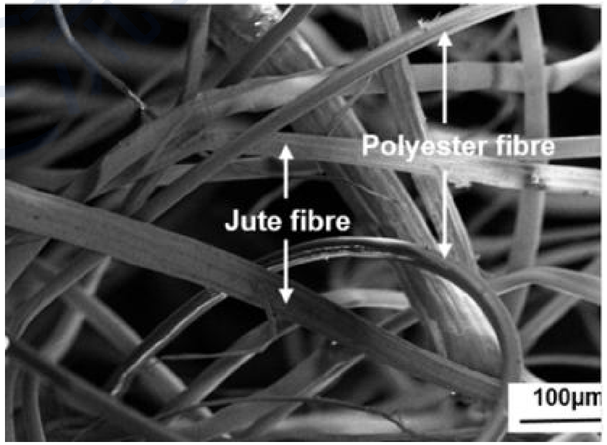
The Technical Failure: Under elevated processing temperatures and pressures, PET/PA6 fibers soften prematurely, leading to a catastrophic collapse in gas permeability and compromised laminate consolidation. 在高温高压固化成型工况下，PET/PA6 聚合物纤维会过早软化，导致透气通道塌陷，进而破坏抽真空路径并影响复材构件的密实度。

● Jute Substitution & Permeability Retention 天然纤维替代与透气率优势

Advanced Material Hybridization 先进生物质材料混配: Eco-Breathers developed by CCIC rely on substituting 40%–60% of the virgin polymer with sustainably sourced Jute Fibres, creating a fully degradable/recyclable composite ancillary infrastructure.

创新中心通过采用可持续**黄麻纤维**替代**40%–60%**的PET，成功研发出完全可降解/可回收的绿色透气毡





Eco-Breather Technology
绿色工艺辅材：生态透气毡：绿色制造、循环经济

- **Green manufacturing: Eco-Breather 生态透气毡助力绿色制造**
- **Jute Substitution & Permeability Retention 天然纤维替代与透气率保持优势**

Superior Thermal Integrity 优异的高温热稳定性

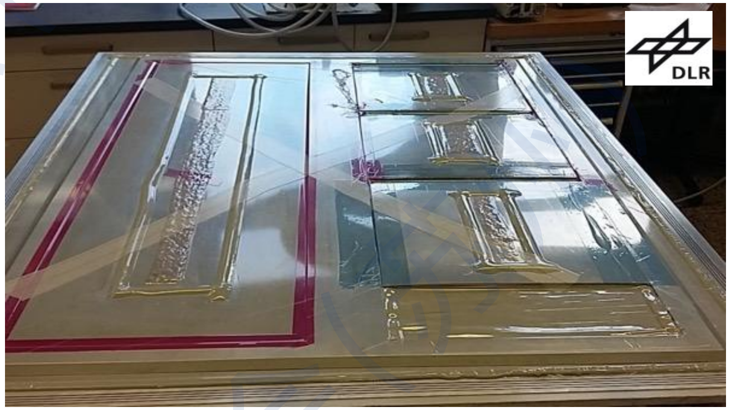
Unlike synthetic polymers, natural jute fibers do not undergo early thermal softening, ensuring the continuous preservation of highly efficient vacuum channels up to 200℃.

与合成聚合物不同，天然黄麻纤维在固化过程中不会发生早期热软化，确保在高达200 ℃的中高温成型工况下，真空排气通道依然保持高度畅通。

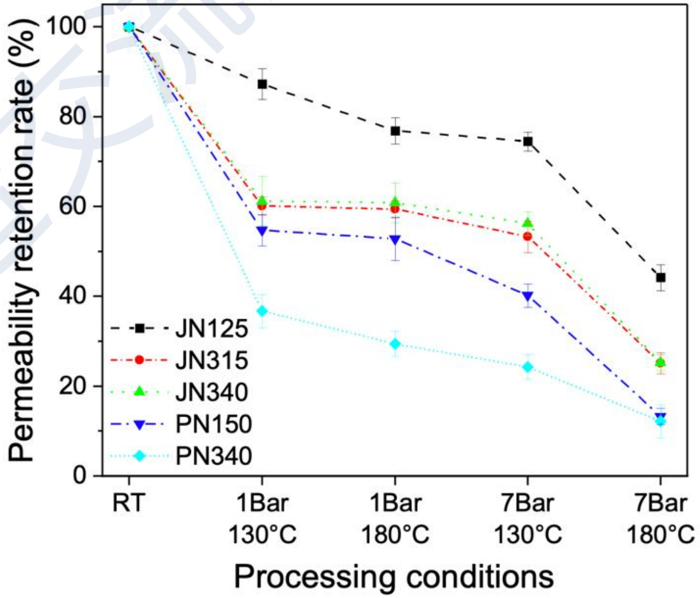
Moisture Management & Enhanced Re-usability 吸湿性管理与循环利用

Jute inherently absorbs approximately 13% moisture, yet precise control variables demonstrate that integrating jute significantly improves gas permeability retention rate through multiple thermal cycles, unlocking great potential for multi-cycle reuse.

尽管黄麻纤维具有约 13% 的天然吸湿性，但精确的工艺控制变量表明，引入黄麻显著提升了多次热循环中的透气率保持率，从而赋予了工艺辅材多次循环使用的巨大潜力。



德国航空航天研究中心（DLR）生态透气毡测试



Ministry of Textiles, Government of India via PWC, 2006
印度政府纺织部官方报告（由普华永道撰写，2006年）

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CCIC 长三角碳纤维及复合材料技术创新中心

Phase of Life Cycle	Impact	Comments
Agricultural phase or phase I	IPCC-GHG effect	The most significant impact in the Jute life cycle is the carbon sequestration by green jute plants in the agricultural stage. Approximately 4.88 tonne of CO2 get sequestered per tonne of raw jute fibre production. However, the anthropogenic methane emission from retting pond in case of conventional retting process also contributes to this impact. But the overall GHG emission impacts becomes negative as the jute plantation acts as a sink for carbon.
Manufacturing Phase or Phase II	Human Toxicity	Uncontrolled use of Jute Batching oil contributes to this impact
Manufacturing phase or	IPCC-GHG effect	CO2 emission due to fossil fuel based energy

Body of same report also suggests Jute cultivation capures **1.5 tonnes CO_2** per tonne dry jute fibre 同一份报告的正文却写着：种植黄麻每吨干纤维仅能捕获1.5吨CO_2

Notes:

- Carbon sequestration c.5 tonnes CO_2/tonne of jute fibre (* difficult to corroborate this figure *) 摘要里写每吨黄麻纤维能固碳约5吨CO_2/吨（* 此数据无法证实）
- Reduction in energy bill vs 100% PET, around 88% for jute 相比100%石油基 PET，采用黄麻可降低约88%的能耗成本
- Re-use potential due to retained gas permeability因其保持了良好的透气性，具备循环再利用的潜力
- Polymer fibre can be substituted by e.g. lignin or recyclate聚合物纤维可被木质素或回收料等进一步替代

Net CO_2 Savings based on 50% jute substitution
基于 50% 黄麻替代的减碳量比

	50% PET/50% Jute
Estimated beather market size	2000 tonnes pa
Embodied carbon PET polymer	2700 tonnes pa
Fibre spinning	9.5 tonnes pa
Jute cultivation + retting	-1300 tonnes pa
Non-woven production	128 tonnes pa
Net CO_2 equivalent	**1537 tonnes**

	100% PETfibre
Estimated beather market size	2000 tonnes pa
Embodied carbon PET polymer	5400 tonnes pa
Fibre spinning	19 tonnes pa
Non-woven production	128 tonnes pa
Net CO_2 equivalent	5547 tonnes

EPA United States Environmental Protection Agency

- A typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year.
- This assumes the average gasoline vehicle on the road today has a fuel economy of about 22.0 miles per gallon and drives around 11,500 miles per year. Every gallon of gasoline burned creates about 8,887 grams of CO_2.

一辆典型的家用车每年排放约 4.6 吨二氧化碳

CF Energy Intensity: High Baseline, High Variability

碳纤维能耗强

■ **The Massive I**

Virgin CFRP produc
966 MJ/kg — nearl
(89.5 MJ/kg).

原生碳纤维复材制备
标准玻纤环氧材料（8

90% Hotspot: Withi
of total energy inte
(oxidation/graphitis

在整个复材供应链中，

Table 1 Total energy consumption per kg carbon fibre

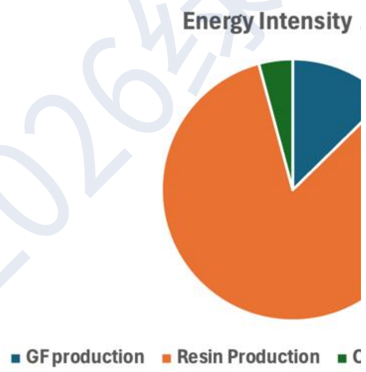
Source	Total Energy [MJ/kg]	Data origin	Comment
Arnold et al. [16]	255	Experimental data, simulation	Heat and electricity
Das [3]	459	Experimental data, databases	Little details about system
Suzuki et al. [17]	286	unclear	No details about system
Liddell et al. [18]	219	Experimental data, databases, estimations	US industry average
Liddell et al. [19]	195	Experimental data, databases, estimations	"State of the art" average
Dér et al. [15]	1150	Experimental data	Incl. peripheral processes

ranging from 195

的波动性与不一致性，

ms from lack of
, and absence of

特异性、能量边界



Glass-Epoxy Composites (89.5 MJ/kg)

Carbon Epoxy Composites (966 MJ/kg)

Impact of Middle East Conflict
中东冲突对材料供应链的冲击

Toray Industries, Inc. (Tokyo, Japan) will introduce **surcharge pricing** on carbon fiber composite materials and other products as an emergency measure to address skyrocketing costs for petrochemical feedstocks and other raw materials driven by the military conflict with Iran and de facto blockade of the Strait of Hormuz.

日本东丽公司宣布，因与伊拉克的军事冲突及霍尔木兹海峡的实质性封锁，导致石油化工原料及其他原材料成本飙升。作为紧急措施，东丽将对碳纤维复合材料等产品加收紧急附加费。

- 中东战争严重破坏了能源基础设施，霍尔木兹海峡面临关闭，推高了油价。但该地区其他出口物资怎么办？
- 除能源外，冲突还打断了甲醇、铝、硫磺和石墨等核心非油大宗商品的供应链，直接冲击了全球制造业和**绿色能源转型**。
- 这些工业基石的断供正在迅速重塑全球供应链（从农业肥料到支撑高科技产业的矿产）

- **War in the Middle East has caused significant damage to energy infrastructure and the near closure of the Hormuz Strait, driving oil prices up, but what about the region's other exports?**
- **Beyond energy, the conflict is disrupting key non-oil commodities – like methanol, aluminium, sulfur and graphite – impacting global manufacturing and the green energy transition.**
- **Disruptions to these industrial essentials are rapidly reshaping global supply chains – from fertilizers for future harvests to minerals driving high-tech industries. Here are nine at the centre of the shift.**

World Economic Form April 9th

Potential energy savings identified

GRP Industry

21% via rollout of industry best practice (7,000 TJ)

28% via successful deployment of ongoing R&D (9,160 TJ)

CFRP Industry

22% via rollout of industry best practice (1,266 TJ)

63% via successful deployment of ongoing R&D (3,619 TJ)

Industry awareness, collaboration, training and technology transfer are critical factors!

行业意识、协同合作、教育培训以及技术转移，都是实现上述目标的关键要素！

DoE Data 2017

Aggregation of marginal gains
边际效益的聚合与微小优势积累

Cyclingweekly.com

Capovelo.com

■ The British Cycling Transformation 英国自行车队的逆袭案例

- UK had won only one Olympic gold since 1908

在2003年之前，自1908年以来的近百年历史中，英国国家自行车队仅获得过一枚奥运金牌。

- David Brailsford took over management in 2003 of UK cycling team. DB’ s philosophy was to seek tiny improvements in every aspect of activity

2003年戴维·布雷尔斯福德爵士接管车队，引入了在每个细微环节都追求 **1%性能提升** 的核心哲学：

  - Electrically heated shorts
  - Alcohol rubbed tyres
  - Optimised massage gel formulation

❑ The team won 8 Gold medals at Beijing 2008

通过这些微小优势的持续聚合，车队实现历史性突破，在 2008 年北京奥运会上狂揽 **8枚金牌。**

Net-Zero Aviation cannot be delivered by a single miracle material; it demands the **aggregation of marginal gains** to eliminate supply chain carbon piece by piece.
绿色航空的“净零”目标无法靠孤立的单一材料实现；它同样是一场**边际效益的聚合战**——必须通过纤维增强体、绿色树脂和绿色制造的系统集成，综合供应链各环节的减碳效益

Vertical optimization
垂直优化（供应链层面的减排潜力）

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- **Global Supply Chain Impact 全球供应链的碳排现实**

8 Global supply chains generate more than 50% of global emissions.

全球 8 大核心供应链贡献了全球**50%以上**的碳排放（数据源自世界经济论坛）。

- **The Automotive Reference 汽车行业的成功先例**

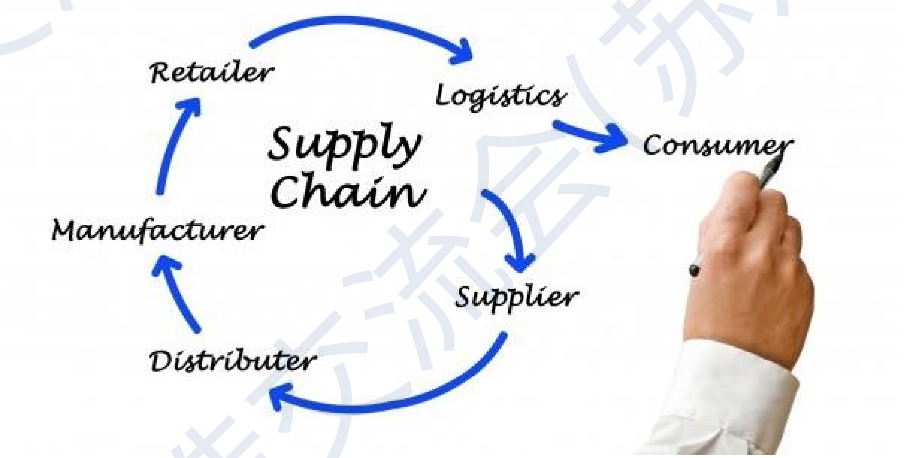
Automotive OEMs have been shown to reduce emissions by approx. 60% via supply chain changes.

经验表明，汽车行业OEM通过重构供应链，已成功实现了**约 60%**的大幅减排。

- **The Cost-Sharing Model 成本分摊与最终消费者的变量关系**

Cost sharing across the chain means only marginal increase in costs to final consumer (1-4%)

若将绿色转型成本在全供应链各环节进行合理分摊，最终传导至终端消费者的成本溢价**仅为1%–4%**。



Carpe diem valuenet

Change requires investment and therefore needs to be data driven!

产业变革需要资本投入，因此必须依靠**数据驱动**！

Where are the low hanging fruit?
寻找“低悬的果实” （用数据找准技术突破口）

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- **LCA Mapping Methodology 依托 LCA 的能耗矢量映射**

Various approaches based on LCA taken to map energy vectors in composites manufacturing.

综合运用多种基于**LCA（生命周期评价）**的分析方法，全面评估复合材料制造全流程中的能耗分布。

- **Sensitivity Variables 核心控制变量关联**

Energy intensity and embedded carbon clearly depend upon formulation and processing of primary materials, intermediates and final product.

材料的能量密集度与内含碳足迹，严格取决于**基础原材料、中间体（如预浸料）到最成品**的配方设计与加工工艺。

- **The Core Question / 战略核心设问（引出数据图表）**

Where are the energy intensive hotspots in our supply chains?

在我们的复合材料供应链中，**高能耗的核心**究竟隐藏在哪里？

注：右侧图表（Hesser et al., 2016）量化对比了不同生产规模下，聚丙烯（PP）和碳纤维增强聚丙烯（CF20PP）在控制、加热、驱动等工艺环节的单位能量消耗（SEC）

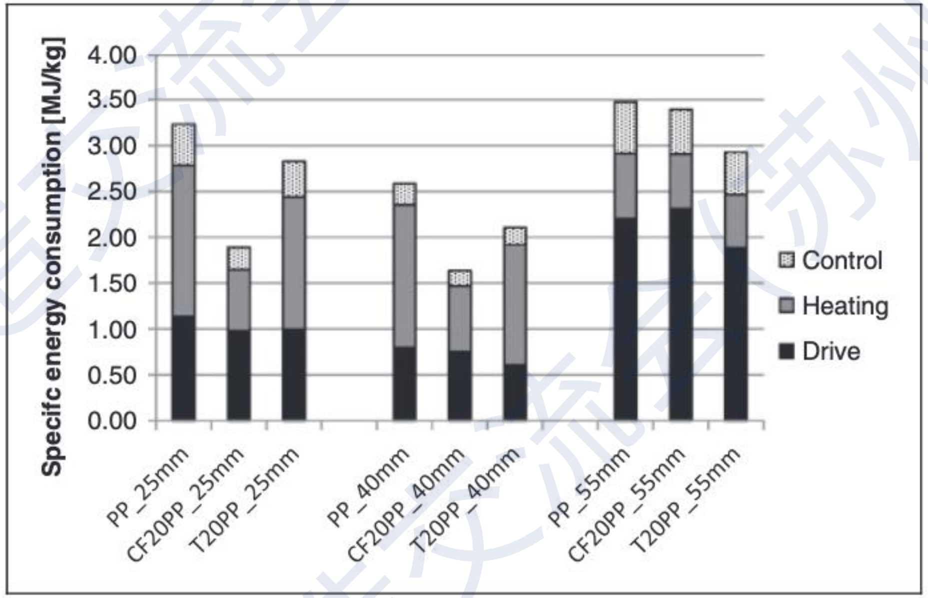


Figure 6. Contributions to the total SEC (MJ/kg): comparison of PP, CF20PP and T20PP on different production scales.

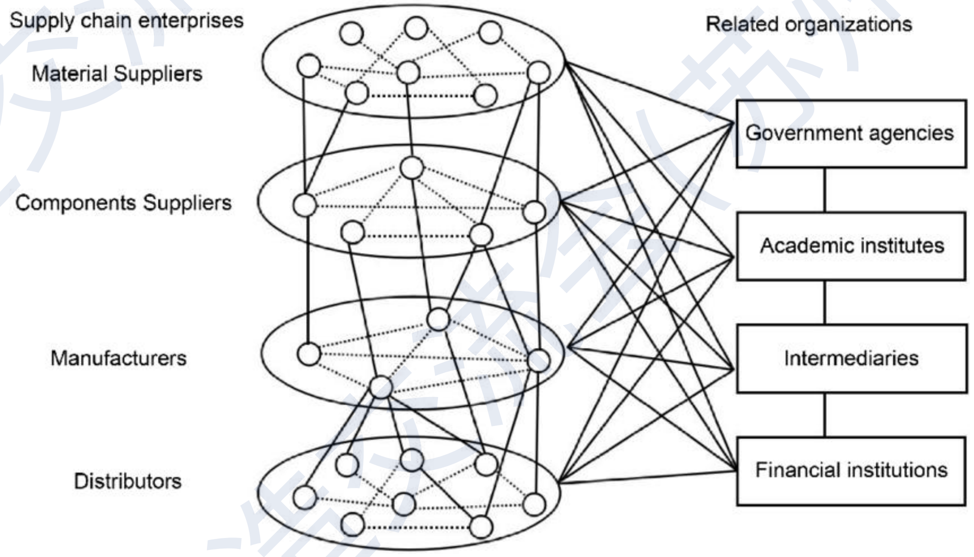
Hesser et al 2016

Reliable decision making requires reliable data – "Garbage in Garbage out"
科学决策始于可靠数据——错误投入必导致错误产出！

Organizational interventions 组织级干预（宏观生态与政策协同）

The 5-Dimension Action Plan 五大维度的落地行动方案

1. Acceleration of switching to green power 加速向绿色电力/**清洁能源结构**转型
2. Enhancement of industry clustering – reduction in product-km 强化**产业集群化布局**，大幅缩短物料运输公里数（降低隐性物流碳排）
3. Supply chain collaboration and joint investment 推动**全供应链的深度协同**与绿色联合投资
4. Tax incentives for incremental resource efficiency 争取针对资源利用率提升的**税收优惠与政策激励**。
5. Enhanced roles for trade associations and regional platforms in advocating Green engineering and supporting transition 强化**行业协会与区域创新平台**在倡导“绿色工程”及支持产业转型中的纽带角色



He, Open Journal of Business and Management (2016)

Conclusions
结论与思考

1. Standardization & Market Penetration 标准规范化与市场渗透

As environmentally driven design planning becomes more important we need greater standardization in impact assessment, materials sourcing and data in order to better drive the penetration of Green Composites.

随着环境驱动型设计规划的战略地位日益凸显，行业亟需在**环境影响评估、原材料采购规范以及底层数据库**方面推进更高标准的规范化，从而有效加速绿色复合材料在航空领域的深度渗透。

2. Urgent Data & Provenance Priorities 数据链与可追溯性构建

Improved data and provenance is especially urgent for:

完善高质量数据链与可追溯性在以下三个核心环节尤为迫切：

- Synthetic fiber manufacture 合成纤维制造：聚焦传统碳纤维生产的高能耗死穴与回收碳纤维的数据闭环。
- Plant fibre cultivation and processing 植物纤维种植与加工：打通农业源头、脱胶工艺到全生命周期的全流程全生命周期追踪。
- Bio-resin renewables content and recyclability 生物基树脂组分与回收：严格测定可再生生物碳含量，并确立最终废弃后的循环可行性。

3. Innovative Commercial Architecture 商业模式与落地机制的创新

Future commercial progress on bio-sourced products will require more innovative business and distribution models

绿色生物基产品未来若想取得长足的商业化进展，不仅取决于材料本身的迭代，更依赖于构建**更具创新性的商业模式**（如供应链全环节的成本合理分摊机制）。

End, Q&A

The statements made herein do not constitute an offer. They are based on the mentioned assumptions and are expressed in good faith. Where the supporting grounds for these statements are not shown, CCIC will be pleased to explain the basis thereof.