

University of Wales Trinity St David

School of Engineering



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Automotive Materials and Sustainability ACHA 6012

Harvey Levell

BEng Motorsport Engineering

2300714

26th April 2026

Contents

1. Introduction.....	4
2. Literature Review	5
3. Sustainability Analysis.....	8
3.1 Lifecycle Assessment Framework.....	8
3.2 Raw Material Extraction and Production.....	8
3.3 Manufacturing Phase.....	9
3.4 Use Phase and Performance Efficiency	9
3.5 End-of-Life and Legislation	9
3.6 Summary.....	10
4. Experimental Methods and Results	11
4.1 Failure Modes.....	11
4.2 Tensile Strength Results.....	12
4.3 Specific Strength.....	17
5. Recommendations.....	18
6. Conclusion	20
7. References	21

Table of Figures

Figure 1 - Manufacturing Process from PAN precursor to Carbon fibres (emobility-engineering, 2025)	5
Figure 2 - Examples of Kevlar being use for a side pod in Formula cars (Kanal, 2025)	6
Figure 3 - Resin Infusion process diagram (Samaro, 2024)	7
Figure 4 - Life Cycle Assessment (LCA) Flow Diagram from Cradle to Grave (CtGr) and Cradle to Cradle (CtC) (Shaik et al., 2018)	8
Figure 5 - Materials post failure left to right: Aluminium 1050 (assumed), Carbon Fibre non-woven mat Bio resin, Carbon Fibre woven Bio resin, Flax woven Bio resin, Flax non-woven Bio resin, Carbon Fibre woven Epoxy resin, Kevlar.	11
Figure 6 - Cabon Fibre Woven comparison with epoxy and bio resin types	13
Figure 7 - Graph comparing carbon fibre woven and none woven stress/strain curve ...	14
Figure 8 - Graph comparing Flax woven and none woven stress/strain curve	15
Figure 9 - Stress/Strain curve for all tested materials	15
Figure 10 - Bar chart demonstrating Specific strength of tested materials	17
Figure 11 - Radar chart demonstrating each attribute of the tested materials using normalised multi-criteria	18

1. Introduction

The motorsport industry faces increasing pressure to reduce its environmental impact whilst maintaining the performance standards. Material selection is central to this, influencing vehicle mass, structural integrity and environmental burden. This report evaluates composite and metallic materials through tensile testing, rule of mixtures analysis and lifecycle assessment, across three axes to identify materials capable of meeting both performance and sustainability requirements aligned with FIA Environmental Accreditation and EU Green Deal objectives (FIA, 2023; European Commission, 2019).

2. Literature Review

Composite materials, defined as two or more constituents producing properties neither could achieve independently (Hull and Clyne, 1996), are fundamental to modern motorsport due to their exceptional strength-to-weight ratio. However, the environmental cost of traditional CFRP has driven significant interest in natural fibre alternatives, particularly flax, now validated at the highest levels of competition.

Carbon fibre is produced from a polyacrylonitrile (PAN) precursor, undergoing stabilisation, carbonisation and graphitisation to align carbon atoms into a graphite structure, responsible for its high axial stiffness and tensile strength (Savage, 2008; McBeath, 2008). The Pyrofil carbon fibre used in this study (Mitsubishi Rayon, 2013) is a PAN-based high-tenacity fibre; standard HT grades such as the TR50S series offer tensile strengths of approximately 4,900 MPa and a tensile modulus of 240 GPa. From a safety perspective, CFRP is unrivalled for impact absorption, achieving specific energy absorption values of 40–70 kJ/kg compared to steel at 12 kJ/kg and aluminium at 20 kJ/kg (Savage, 2008).

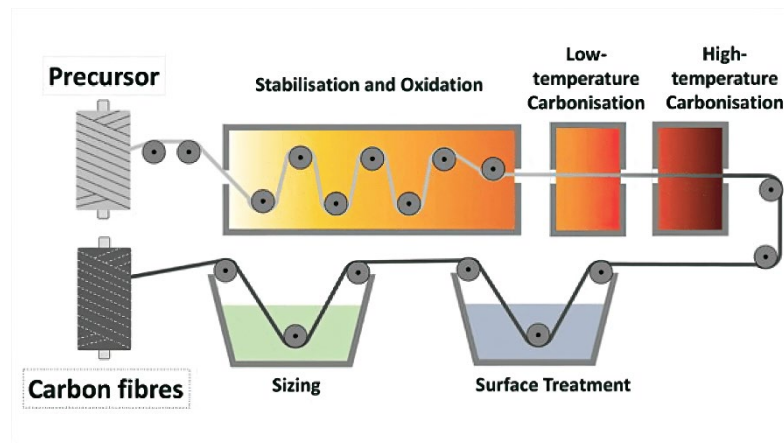


Figure 1 - Manufacturing Process from PAN precursor to Carbon fibres (emobility-engineering, 2025)

Two fibre architectures are evaluated in this study. The twill 2-2 woven carbon fabric interlaces tows in a regular offset pattern, producing excellent drapeability for complex motorsport geometries. The CF-NWM non-woven mat (Easy Composites, 2024) consists of randomly oriented short fibres from 100% recycled carbon fibre, producing quasi-isotropic properties at lower absolute strength values, a distinction with significant sustainability implications discussed in Section 3.

Flax is a naturally harvested bast fibre whose hierarchical microstructure consists of cellulose microfibrils arranged helically within a hemicellulose and lignin matrix (Baley, 2002). This architecture is responsible for flax's mechanical stiffness and excellent vibration damping particularly relevant to motorsport where NVH management is critical for driver feedback and component fatigue life (McBeath, 2008). The FlaxDry BL200 twill fabric (EcoTechnilin, 2023) achieves tensile strengths of 58–61 MPa and a Young's Modulus of 6–7 GPa at a fibre volume fraction of 29%. While lower than carbon fibre in absolute terms, the lower fibre density of 1.45 g/cm³ versus 1.8 g/cm³ means specific properties are more competitive than raw values suggest. The FibriMat F300 non-woven mat (EcoTechnilin, 2023) achieves 37–44 MPa tensile

strength at an 18% fibre volume fraction, lower than its woven equivalent due to the discontinuous fibre architecture limiting load transfer efficiency.



Figure 2 - Examples of Flax being use for a side pod in Formula cars (Kanal, 2025)

Flax composites are now proven at the highest levels of competition demonstrated by figure 2. Super Formula confirmed a 70% flax/30% carbon hybrid construction for its SF23 chassis, demonstrating that sustainable materials are viable at elite performance levels (CompositesWorld, 2022). Flax composites also fail progressively rather than splintering, reducing secondary injury risk to drivers and marshals, a safety advantage over CFRP in impact events.

Two matrix systems are compared in this study, both manufactured by Easy Composites. The IN2 conventional epoxy is a low viscosity system (200–450 mPa.s) achieving a cured tensile strength of 68.5–76 MPa and flexural modulus of 3,100–3,500 MPa. The IB2 bio-epoxy derives its epichlorohydrin from renewable plant-based glycerol rather than petroleum, achieving approximately 31% plant-based content. Its cured properties, 68 MPa tensile strength and 3.07 GPa flexural modulus, are broadly equivalent to IN2, meaning sustainability gains come at negligible mechanical cost (Easy Composites, 2024).

All specimens were manufactured by resin infusion, demonstrated by figure 3, a closed-mould process where liquid resin is drawn through dry fibre reinforcement under vacuum pressure, eliminating voids and achieving a controlled fibre volume fraction (McBeath, 2008). Compared to prepreg/autoclave processing, infusion requires no refrigerated material storage, no autoclave, and reduces VOC emissions, making it the practical and economically viable manufacturing route. The three-ply 45° layup used for twill specimens moves laminate behaviour towards quasi-isotropic, meaning experimental results are expected to fall between the longitudinal and transverse datasheet values, a relationship validated through Rule of Mixtures calculations in the experimental section.

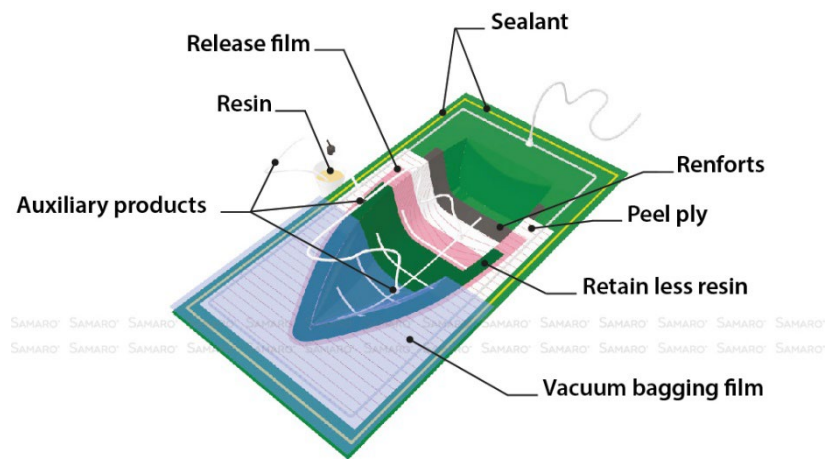


Figure 3 - Resin Infusion process diagram (Samaro, 2024)

3. Sustainability Analysis

3.1 Lifecycle Assessment Framework

The environmental impact of composite materials must be evaluated across their entire lifecycle. A methodology known as cradle-to-grave Life Cycle Assessment (LCA) in figure 4, governed by ISO 14040 and ISO 14044 (ISO, 2006). In motorsport, LCA enables data-driven material selection decisions that balance mechanical performance against environmental cost.

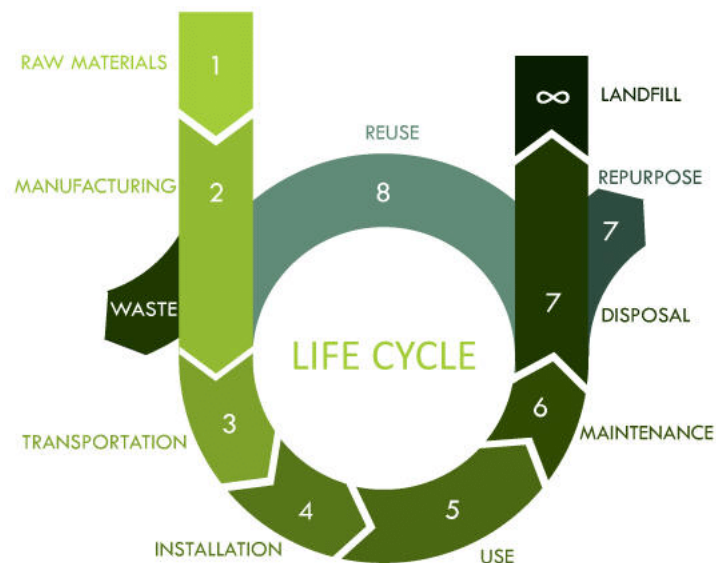


Figure 4 - Life Cycle Assessment (LCA) Flow Diagram from Cradle to Grave (CtGr) and Cradle to Cradle (CtC) (Shaik et al., 2018)

3.2 Raw Material Extraction and Production

The environmental burden of carbon fibre begins at the precursor stage. PAN precursor production is energy-intensive, consuming an estimated 183–286 MJ/kg and producing approximately 20–31 kgCO₂eq/kg of finished fibre (Das, 2011), considerably higher than aluminium at 9.82 kgCO₂eq/kg for secondary production. European flax, by contrast, sequesters atmospheric CO₂ during growth, requires no irrigation and minimal pesticide application, resulting in a cradle-to-gate carbon footprint estimated at up to 85% lower than equivalent carbon fibre parts (Bcomp, 2022). The IB2 bio-epoxy further reduces fossil fuel dependency by substituting petroleum-derived epichlorohydrin with plant-based glycerol, achieving approximately 31% bio-based content (Easy Composites, 2024). The flax/IB2 combination, therefore, minimises petrochemical inputs at both fibre and matrix stage simultaneously, representing the most environmentally coherent system tested.

The recycled CF-NWM occupies a meaningful middle ground, a virgin carbon fibre production is avoided, though the pyrolysis recycling process itself consumes energy and produces emissions, meaning recycled CF is an improvement over virgin material rather than a carbon-neutral solution (McBeath, 2008).

3.3 Manufacturing Phase

Vacuum resin infusion, used to manufacture all specimens in this study, reduces VOC emissions relative to open wet-layup and eliminates the energy-intensive autoclave curing required for prepreg systems that requiring significantly greater energy input and extended cure cycles. This is a significant reduction in manufacturing phase energy consumption relevant to motorsport supply chains increasingly scrutinised under governing body environmental programmes.

3.4 Use Phase and Performance Efficiency

The experimental results demonstrate that carbon twill composites achieved average tensile strengths of 400 MPa (IN2) and 419.5 MPa (IB2), approximately 3.5 times the aluminium baseline of 115 MPa. At less than half the cross-sectional area, this illustrates the fundamental mass-saving case for composites in motorsport. Flax woven composite achieved 84.5 MPa on average, lower than aluminium in absolute terms, but at a fibre density of 1.45 g/cm³ versus aluminium's 2.70 g/cm³, specific mechanical properties remain competitive for non-structural applications (Baley, 2002; Mallick, 2007).

This is consistent with real-world deployment, where flax is validated for bodywork, aerodynamic panels and trim, applications where NVH damping and sustainability credentials are prioritised over maximum tensile strength (CompositesWorld, 2022).

3.5 End-of-Life and Legislation

End-of-life disposal is the most significant sustainability challenge for conventional CFRP. The EU End-of-Life Vehicles Directive 2000/53/EC mandates that 95% of vehicle mass must be recoverable and 85% recyclable by weight (European Parliament, 2000). Thermoset CFRP presents a compliance challenge, mechanical recycling degrades fibre properties, while pyrolysis recovers fibre but destroys the matrix.

The carbon fibre non-woven mat, manufactured from recycled carbon fibre, demonstrates one credible circular economy pathway for carbon composites. Flax composites offer a more favourable end-of-life profile, being a natural cellulosic material, flax fibre is biodegradable and can be thermally recovered with minimal toxic residue. However, thermoset bio-resins remain difficult to mechanically recycle, limiting full circularity (Gay and Hoa, 2007).

The FIA Environmental Accreditation Programme and the adoption of sustainable materials across Formula E, Extreme E and GT4 reflect a regulatory direction aligned with EU Green Deal objectives and the UK's net zero 2050 commitment. The validation of flax composites from the BMW M4 GT4 to Super Formula's SF23 demonstrates these legislative pressures need not compromise competitive performance (FIA, 2023; Bcomp, 2022; CompositesWorld, 2022).

3.6 Summary

Across the lifecycle, the flax/IB2 system offers the most sustainable option tested, renewable raw materials, low-energy manufacturing, competitive specific properties for non-structural applications and a favourable end-of-life profile. Recycled CF non-woven mat offers meaningful improvement over virgin CFRP whilst retaining carbon fibre performance characteristics. Conventional carbon twill remains the highest-performing structural option but carries the greatest environmental burden across the lifecycle. The experimental section that follows quantifies these performance differences and validates them against manufacturer datasheet values.

4. Experimental Methods and Results

Tensile testing was conducted using a Denison universal testing machine in accordance with the protocol established for this module. All composite specimens were pre-manufactured using vacuum resin infusion, with woven reinforcements laid up at 45 degrees to the loading axis across three plies and non-woven reinforcements tested as single-ply laminates.



Figure 5 - Materials post failure left to right: Aluminium 1050 (assumed), Carbon Fibre non-woven mat Bio resin, Carbon Fibre woven Bio resin, Flax woven Bio resin, Flax non-woven Bio resin, Carbon Fibre woven Epoxy resin, Kevlar.

Results were collated across the full cohort to produce a broad dataset. Interquartile range (IQR) outlier removal was applied to eliminate anomalous readings attributable to sample preparation inconsistencies across groups (Hull and Clyne, 1996). Five Kevlar specimens were additionally excluded based on cross-sectional areas of approximately 2 mm², which is physically inconsistent with the expected geometry and indicative of single-tow measurement error rather than composite failure.

Specimen dimensions including cross-sectional area were recorded prior to each test. Failure mode was observed directly during testing and documented through post-test examination of fractured specimens.

4.1 Failure Modes

Aluminium specimens exhibited characteristic ductile failure, with visible necking and elongation of the gauge section prior to fracture and a clean diagonal shear break consistent with plastic deformation under tensile loading. All composite specimens failed in a brittle manner with no visible plastic deformation, consistent with the behaviour of thermoset matrix composites reported by Mallick (2007).

Carbon fibre woven specimens, both with IN2 and IB2 resin, failed suddenly with an audible snap, displaying linear fracture surfaces and localised fibre splitting. This brittle failure mode is characteristic of CFRP under off-axis loading, where interlaminar shear stresses exceed matrix strength before the fibres themselves reach their tensile limit (Gay and Hoa, 2007). Carbon non-woven specimens exhibited a comparatively jagged fracture across the gauge section, consistent with the random fibre orientation distributing stress randomly across the cross-section.

Flax woven specimens showed a more progressive failure relative to carbon, with visible fibre pull-out at the fracture surface indicative of fibre-matrix debonding prior to final fracture, a behaviour reported by Baley (2002) as characteristic of cellulosic natural fibres. Flax non-woven specimens fractured cleanly with minimal fibre pull-out, reflecting the shorter, randomly oriented fibre architecture of the FibriMat F300 (EcoTechnilin, 2023). Kevlar specimens displayed the distinctive fibrillation fracture mode associated with aramid fibres, with white fibrous strands visible at the break and no clean fracture surface, consistent with the energy-absorbing failure mechanism that makes Kevlar effective in impact-critical applications (Mallick, 2007).

4.2 Tensile Strength Results

Mean tensile strength values for the cleaned class dataset are presented in Table 1 alongside standard deviation, coefficient of variation (CoV), specific strength, datasheet or rule of mixtures reference values, and percentage deviation from those references.

Table 1 - Experimental and theoretical values for materials tested

Material	Calculated (GPa)		Datasheet	Experimental T.c	Experimental UTS (MPa)	Datasheet/ROM UTS (MPa)	% diff to datasheet?ROM	Specific Strength (MPa*cm ³ /g)	CoV(%) (UTS)
	T.c upper	T.c lower	T.c (GPa)						
Aluminium (1050)	x	x	x	52.13	116.30	117.50	-1.10	43.10	1.80
Carbon woven + Epoxy	118.55	6.12	x	60.46	399.90	2486.00	-83.90	273.90	11.80
Carbon woven + Bio	118.52	6.00	x	65.56	374.90	2484.00	-84.90	255.00	19.00
Carbon non woven + Bio	x	x	35.00	6.44	175.70	290.00	-39.40	116.40	23.20
Flax Woven + Bio	x	x	6.50	1.67	87.10	59.50	46.40	71.60	10.40
Flax nonwoven + Bio	x	x	5.00	5.22	43.30	40.50	6.90	36.70	23.80
Kevlar Woven	57.52	5.92	x	31.17	290.80	1534.00	-81.00	227.20	19.80

Aluminium recorded a mean tensile strength of 116.3 MPa with a CoV of 1.8%, confirming the high consistency expected of a wrought metal baseline and validating the test setup. This result is 1.1% below the typical datasheet value of 117.5 MPa for commercial 1050 series aluminium (Smith Metals, 2024), a small deviation attributable to alloy grade uncertainty. This grade was assumed based on its consistency with experimental results and typical use cases.

Carbon woven composites produced the highest tensile strengths of all materials tested, with IN2 achieving a mean of 399.9 MPa and IB2 achieving 374.9 MPa. Figure 6 illustrates the response of woven systems, both exhibit a linear elastic region followed by sudden brittle fracture with no yield plateau. The gradient of the linear region reflects the experimentally recorded modulus values of 60.46 GPa and 65.56 GPa respectively, which fall between the longitudinal upper bound of 118.55 GPa and 118.52 GPa calculated using equation (1) and the transverse lower bound of 6.12 GPa and 6.00 GPa calculated using equation (2), as expected for specimens loaded at 45 degrees.

The CoV values of 11.8% and 19.0% respectively suggest greater manufacturing variability in the specimens, likely reflecting differences in infusion behaviour rather than a fundamental property difference between the resins. Both results represent approximately 84% below the longitudinal tensile strength upper bound of approximately 2,485 MPa calculated using equation (3), which is entirely consistent with the 45 degree fibre orientation of the test specimens. At 45 degrees, load is carried primarily through the matrix and fibre-matrix interface rather than along the fibre axis, reducing effective strength significantly below the longitudinal prediction (Hull and Clyne, 1996).

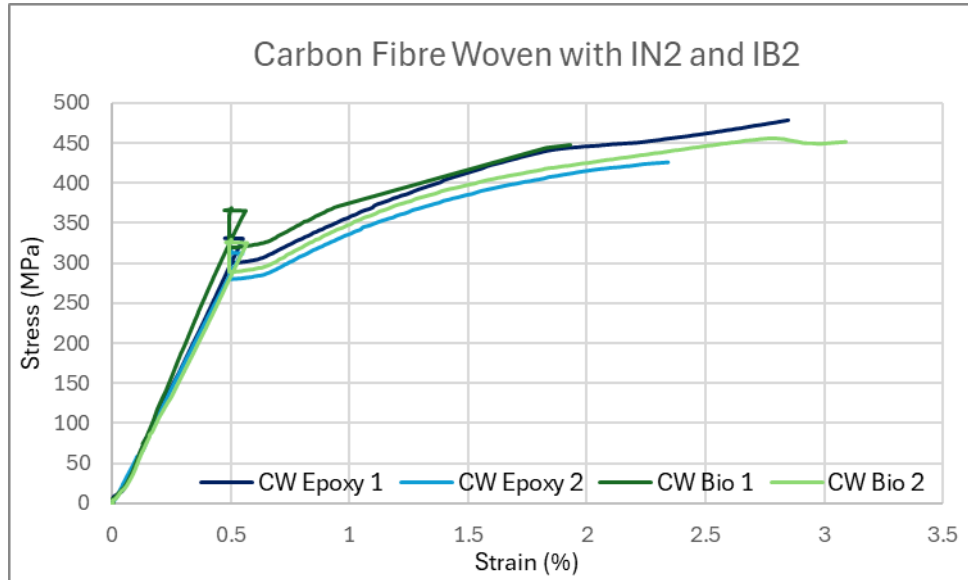


Figure 6 - Carbon Fibre Woven comparison with epoxy and bio resin types

$$E_{(\text{composite longitudinal})} = (\text{Volume Fraction}_{\text{Particle}} \times E_{\text{Particle}}) + (\text{Volume Fraction}_{\text{Matrix}} \times E_{\text{matrix}}) \quad (1)$$

$$1/E_{\text{composite transverse}} = (\text{Volume Fraction}_{\text{Particle}} \div E_{\text{Particle}}) + (\text{Volume Fraction}_{\text{Matrix}} \div E_{\text{matrix}}) \quad (2)$$

$$\sigma_{cl} = (\text{Fibre Volume Fraction} \times \text{Fibre Tensile Strength}) + (\text{Matrix Volume Fraction} \times \text{Matrix Tensile Strength}) \quad (3)$$

Carbon non-woven specimens recorded a mean of 175.7 MPa, 39.4% below the CF-NWM datasheet composite value of 290 MPa (Easy Composites, 2024). Figure 7 demonstrates the effect of fibre architecture on stress-strain behaviour, showing that carbon non-woven specimens achieve a lower peak stress than carbon woven specimens using the same resin, with a less steep initial gradient consistent with the lower experimental modulus of 6.44 GPa compared to 65.56 GPa. This deviation from the datasheet is attributable to differences in manufacturing process: the datasheet specifies compression moulding at 30% fibre volume fraction, whereas vacuum infusion as used in this study typically achieves lower consolidation pressures and may result in a lower effective V_f and higher void content (Mallick, 2007).

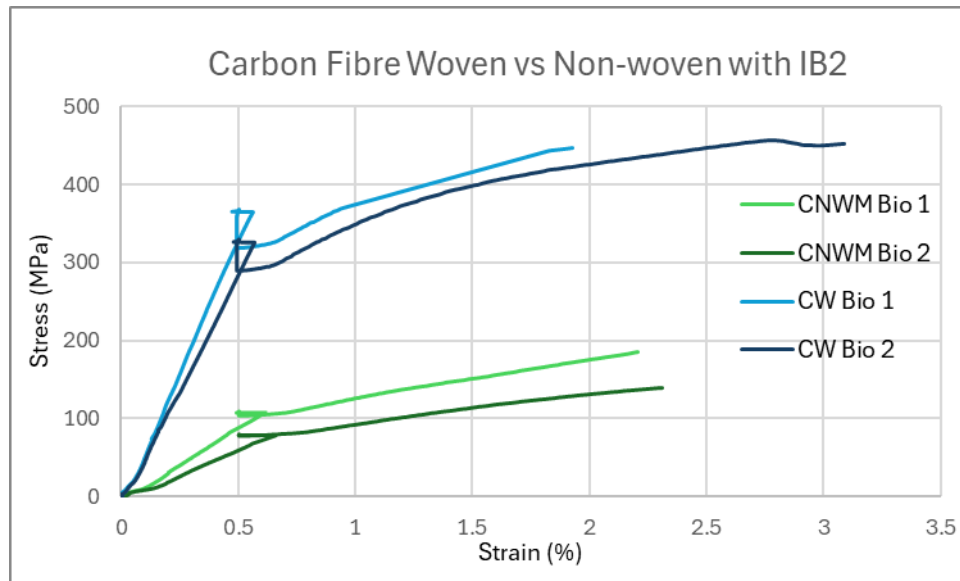


Figure 7 - Graph comparing carbon fibre woven and none woven stress/strain curve

Flax woven specimens produced a mean tensile strength of 87.1 MPa, 46.4% above the datasheet value of 59.5 MPa at $V_f = 29\%$ (EcoTechnilin, 2023). Figure 8 illustrates the architecture effect within flax, showing that the woven specimens achieve a higher peak stress and steeper initial gradient than the non-woven specimens, consistent with the higher V_f and more ordered fibre arrangement. The datasheet quotes properties in individual directions, whereas the 45-degree layup in this study distributes load across both simultaneously, which may produce a higher combined response than either single direction (EcoTechnilin, 2023). The CoV of 10.4% is comparable to the carbon woven IN2 result, suggesting natural fibre woven composites can achieve a consistency competitive with synthetic fibre systems, supporting the findings of Baley (2002).

Flax non-woven specimens recorded 43.3 MPa, within 6.9% of the datasheet value of 40.5 MPa (EcoTechnilin, 2023). This close agreement across a class dataset of 19 specimens provides strong validation of both the test methodology and the datasheet data for this material. The experimental modulus of 5.22 GPa closely matches the stated datasheet value of 5 GPa, providing further confidence in the result.

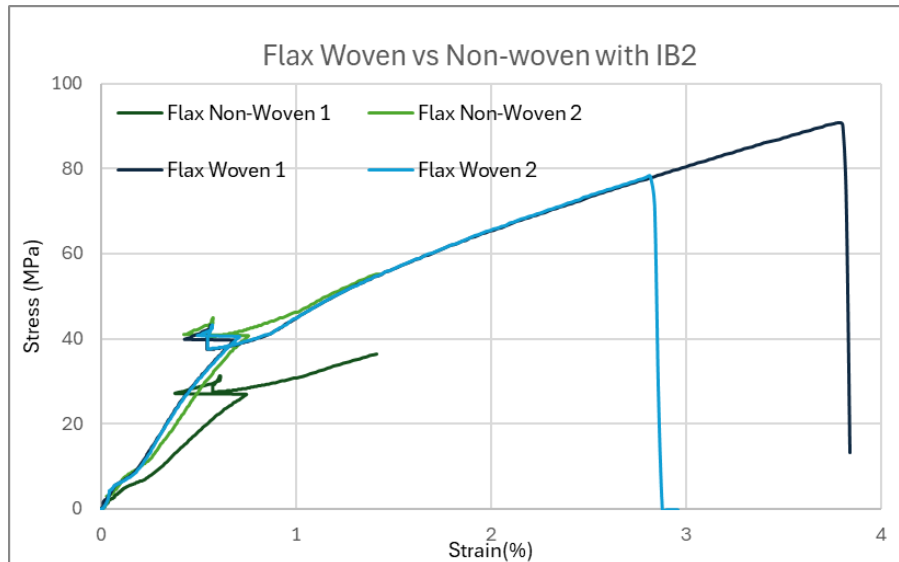


Figure 8 - Graph comparing Flax woven and none woven stress/strain curve

Kevlar specimens produced a mean tensile strength of 290.8 MPa, with a CoV of 19.8% reflecting the inherent variability in aramid composite testing and the relatively small, cleaned sample size of 13. Figure 9 presents the fibre type comparison, showing the Kevlar stress-strain curve exhibiting a higher failure strain than the carbon woven specimens and a more gradual post-peak load drop, consistent with the fibrillation failure mode observed during testing and the energy-absorbing characteristics of aramid fibres reported by Mallick (2007).

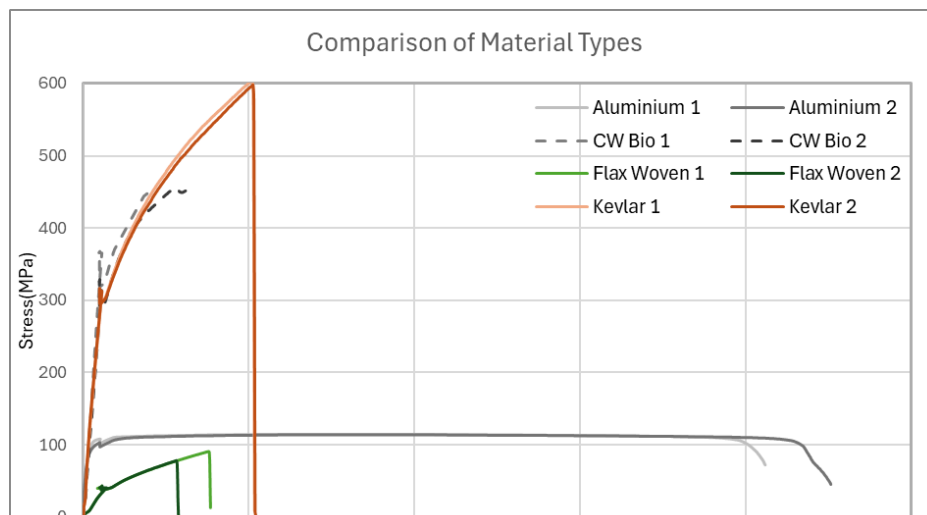


Figure 9 - Stress/Strain curve for all tested materials

Aluminium exhibits significantly greater strain at failure than all composite specimens, a consequence of its FCC crystal structure permitting dislocation movement and plastic deformation, a mechanism absent in the crosslinked thermoset epoxy matrix of all composite materials tested (Callister and Rethwisch, 2018).

4.3 Specific Strength

Specific strength, defined as tensile strength divided by composite density, provides a more relevant performance metric for motorsport applications where mass reduction is a primary design objective (McBeath, 2008). Composite densities were calculated using the rule of mixtures for density where datasheet composite density was unavailable. Results are illustrated in figure 10.

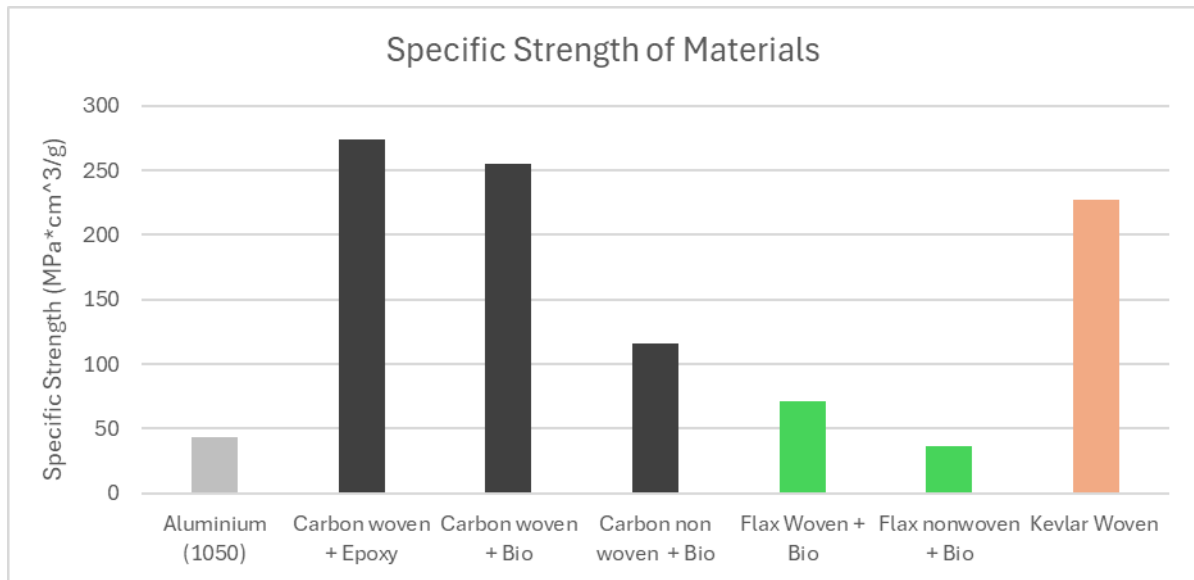


Figure 10 - Bar chart demonstrating Specific strength of tested materials

Carbon woven composites achieved the highest specific strength of all materials tested at 273.9 and 255.0 MPa·cm³/g for IN2 and IB2 respectively, over six times greater than aluminium at 43.1 MPa·cm³/g. This result demonstrates that the performance advantage of CFRP in motorsport is driven not only by absolute strength but by the combination of high strength and low density (Savage, 2008).

Kevlar achieved a specific strength of 227.2 MPa·cm³/g, competitive with carbon composites and reflecting its well-established role in impact and ballistic applications. Flax woven composite achieved a specific strength of 71.6 MPa·cm³/g, 66% higher than aluminium despite its lower absolute tensile strength, reinforcing the case for natural fibre composites in weight-sensitive but non-structural applications (Bcomp, 2022). Notably, flax non-woven is the only composite material to fall below the aluminium baseline at 36.7 MPa·cm³/g, indicating that the non-woven architecture at 18% Vf does not provide a weight-saving advantage over conventional metal construction.

5. Recommendations

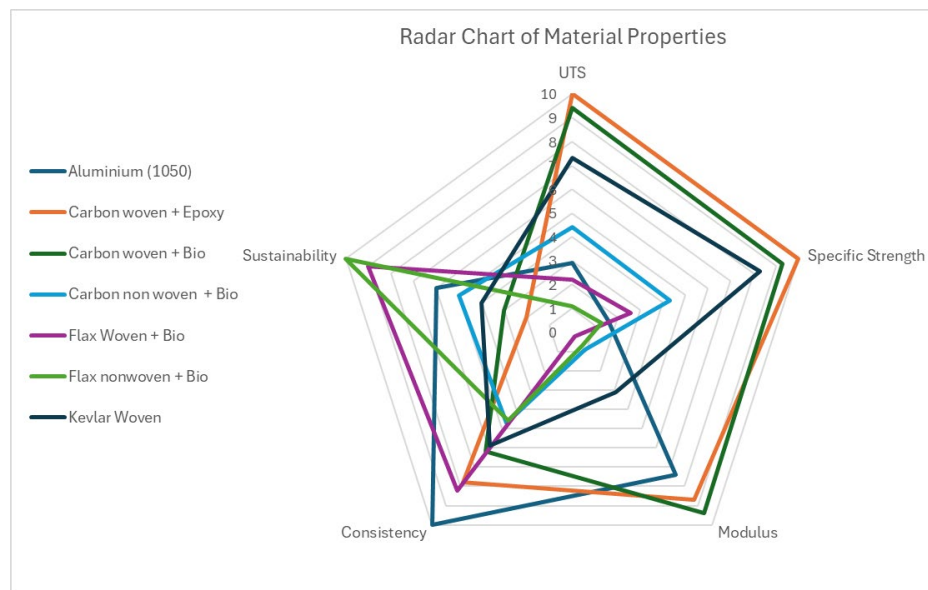


Figure 11 - Radar chart demonstrating each attribute of the tested materials using normalised multi-criteria

No single material tested is optimal across all performance criteria, and selection must balance mechanical performance against lifecycle environmental impact.

Figure 11 shows mechanical values normalised from experimental dataset results (0–10 scale). Sustainability scores are qualitative estimates derived from the lifecycle assessment in Section 2, where higher scores indicate lower environmental impact.

For primary structural applications, carbon woven composite with IB2 bio-epoxy is recommended over IN2. The resin comparison demonstrates only a 6.3% reduction in tensile strength when substituting IN2 for IB2, whilst delivering 31% bio-based matrix content at negligible mechanical cost (Easy Composites, 2024). Where carbon fibre is required, IB2 represents a straightforward sustainability improvement with negligible structural compromise.

The architecture comparison consistently shows woven reinforcements outperform non-woven equivalents regardless of fibre type. Non-woven materials are therefore recommended only for secondary or cosmetic applications, with recycled CF-NWM suited to bulking layers within hybrid laminates where its circular economy credentials are an advantage without relying on it as a primary load-bearing material (Krauklis et al., 2025).

For non-structural applications, flax woven is recommended. Its specific strength of $71.6 \text{ MPa} \cdot \text{cm}^3/\text{g}$ exceeds aluminium by 66%, its CoV of 10.4% is competitive with synthetic fibre systems, and its end-of-life profile is the most favourable of all materials tested. Real-world validation confirms viability at competition standard (Bcomp, 2022; CompositesWorld, 2022).

Kevlar is recommended for impact-critical components such as safety cells, where its fibrillation failure mode and specific strength of $227.2 \text{ MPa} \cdot \text{cm}^3/\text{g}$ provide superior energy absorption relative to carbon at equivalent weight (Mallick, 2007).

Aluminium is not recommended for structural motorsport applications given its specific strength of $43.1 \text{ MPa}\cdot\text{cm}^3/\text{g}$ is exceeded by all composites except flax non-woven. It remains appropriate for non-structural fixings and brackets where composite manufacturing is not cost-effective.

Future research should address the limitations identified in this study. Standardised specimen geometry and controlled fibre volume fraction verification across groups would reduce the CoV values observed, particularly for Kevlar (19.8%) and carbon woven IB2 (19.0%). Testing at 0° and 90° fibre orientations would allow direct validation of the full ROM bounds rather than relying on the 45° intermediate case alone. Fatigue testing and impact resistance characterisation of the flax/IB2 system would further strengthen the case for its adoption in non-structural motorsport applications, where cyclic loading from aerodynamic and vibration inputs is a primary design consideration.

6. Conclusion

Tensile testing of seven materials confirmed carbon fibre woven composites as the highest performing system, achieving 399.9 MPa and a specific strength of 273.9 MPa·cm³/g, over six times the aluminium baseline.

Substituting IN2 for IB2 bio-epoxy reduced tensile strength by only 6.3% whilst delivering 31% bio-based matrix content, demonstrating that sustainability gains need not compromise structural performance. Flax woven composite with IB2 achieved a specific strength 66% above aluminium at 71.6 MPa·cm³/g, validating its application in non-structural motorsport components.

Rule of mixtures calculations confirmed experimental moduli falling between longitudinal and transverse bounds for all woven materials, consistent with the 45° layup.

Across all materials, woven architectures outperformed non-woven equivalents by a factor of approximately two regardless of fibre type, and IQR outlier removal across a class dataset of up to 38 specimens ensured statistical robustness. The flax/IB2 combination and recycled CF-NWM represent the most viable pathways towards meeting FIA environmental accreditation targets and EU Green Deal objectives without compromising competitive performance.

7. References

Baley, C. (2002) 'Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase', *Composites Part A: Applied Science and Manufacturing*, 33(7), pp. 939–948.

Bcomp (2022) *Ready for Series Production: BMW Group Achieves Major Breakthrough with Natural Fiber Composites*. Available at: <https://www.press.bmwgroup.com/global/article/detail/T0450786EN>

Callister, W.D. and Rethwisch, D.G. (2018) *Materials Science and Engineering: An Introduction*. 10th edn. Hoboken: Wiley.

CompositesWorld (2022) *Super Formula, Bcomp Announce Sustainable Fiber Composite Bodywork*. Available at: <https://www.compositesworld.com/news/super-formula-bcomp-announce-sustainable-fiber-composite-bodywork>

Das, S. (2011) 'Life cycle assessment of carbon fiber-reinforced polymer composites', *International Journal of Life Cycle Assessment*, 16(3), pp. 268–282.

Easy Composites (2024) *CF-NWM Carbon Fibre Non-Woven Mat Technical Data Sheet*. Stoke-on-Trent: Easy Composites Ltd.

Easy Composites (2024) *IB2 Epoxy Infusion Bio Resin Technical Data Sheet*. Stoke-on-Trent: Easy Composites Ltd.

Easy Composites (2024) *IN2 Epoxy Infusion Resin Technical Data Sheet*. Stoke-on-Trent: Easy Composites Ltd.

Easy Composites (2024) *K-22-300-100 Kevlar 49 Twill Weave Fabric Technical Data Sheet*. Stoke-on-Trent: Easy Composites Ltd. Available at: <https://media.easycomposites.eu/datasheets/EC-TDS-300g-Twill-Weave-Kevlar-Cloth.pdf>

EcoTechnilin (2023) *FibriMat F300 Technical Data Sheet*. Valliquerville: EcoTechnilin.

EcoTechnilin (2023) *FlaxDry BL200 Technical Data Sheet*. Valliquerville: EcoTechnilin.

Emobility-engineering (2025) *Structural Carbon Fibre: Advancing Structural Batteries for evs, E*. Available at: <https://www.emobility-engineering.com/structural-carbon-fibre-battery-research/> (Accessed: 26 April 2026).

European Commission (2019) *The European Green Deal*. COM(2019) 640 final. Brussels: European Commission. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN>

European Parliament (2000) *Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles*. Official Journal of the European Communities, L 269, pp. 34–43. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0053>

FIA (2023) *FIA Environmental Accreditation Programme*. Available at: <https://www.fia.com/fia-environmental-accréditation>

Gay, D. and Hoa, S.V. (2007) *Composite Materials: Design and Applications*. 2nd edn. Boca Raton: CRC Press.

HM Government (2019) *Net Zero: The UK's Contribution to Stopping Global Warming*. London: Committee on Climate Change. Available at: <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming>

Hull, D. and Clyne, T.W. (1996) *An Introduction to Composite Materials*. 2nd edn. Cambridge: Cambridge University Press.

ISO (2006) ISO 14040: Environmental Management — Life Cycle Assessment — Principles and Framework. Geneva: International Organisation for Standardisation.

ISO (2006) *ISO 14044: Environmental Management — Life Cycle Assessment — Requirements and Guidelines*. Geneva: International Organisation for Standardisation.

Kanal (2025) *This carbon fibre alternative went from ski slopes to formula 1 circuits*. Available at: <https://www.raceteq.com/articles/2025/08/carbon-fibre-natural-bcomp> (Accessed: 26 April 2026).

Krauklis, A.E., Karl, C.W., Gagani, A.I. and Jørgensen, J.K. (2025) 'A comparative environmental and economic analysis of CFRP recycling processes', *Journal of Composites Science*, 9(1), p. 39.

Mallick, P.K. (2007) *Fiber Reinforced Composites: Materials, Manufacturing and Design*. 3rd edn. Boca Raton: CRC Press.

McBeath, S. (2008) *Competition Car Composites: A Practical Handbook*. Sparkford: Haynes Publishing.

Mitsubishi Rayon Co., Ltd. (2013) *Pyrofil — Typical Properties of Carbon Fibre*. Tokyo: Mitsubishi Rayon Co., Ltd.

Samaro (2024) *The Infusion Process Step by Step* Available at: <https://www.samaro.fr/en/news/the-infusion-process-step-by-step/>

Savage, G. (2008) *Composite Materials Technology in Formula 1 Motor Racing. Honda Racing F1*. Available at: [https://www.formula1-dictionary.net/Big/Composite%20Materials%20Technology%20in%20Formula%201%](https://www.formula1-dictionary.net/Big/Composite%20Materials%20Technology%20in%20Formula%201%20)

Shaik, Ayesha & Wong, M L Dennis & Choo, Chee Ming. (2018). *Environmental Life Cycle Assessment of a Standalone Hybrid Energy Storage System for Rural Electrification*.

Smith Metals (2024) *1050A Aluminium Technical Datasheet*. Available at: <https://www.smithmetal.com/pdf/aluminium/1xxx/1050a.pdf>