

University of Wales Trinity Saint David

Wales Institute of Science and Art



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

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Harry Rogers

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1 Introduction

Composite materials are used widely in automotive, motorsport and motorcycle engineering because high stiffness and strength can be achieved at relatively low mass. This is particularly valuable in applications where structural efficiency, crash performance and vehicle dynamics are strongly influenced by weight. However, material selection is no longer governed by mechanical performance alone. Increasing attention is now being given to embodied carbon, recyclability, end-of-life recovery and the wider sustainability of manufacturing routes, especially where conventional carbon-fibre systems are compared with natural-fibre and bio-resin alternatives.

This report evaluates the materials testing and sustainability of a selected group of composite materials. The study considers aluminium as a conventional benchmark together with carbon woven bio-resin, carbon woven epoxy, carbon non-woven bio-resin, flax woven bio-resin, flax non-woven bio-resin and Kevlar woven bio-resin. A literature review is first used to establish the role, structure, properties and manufacturing characteristics of these materials. A sustainability analysis is then carried out to compare their lifecycle implications in terms of resource extraction, manufacturing impact, recyclability, end-of-life disposal and current industry direction. Experimental tensile testing is subsequently examined using representative stress-strain curves and extracted material properties, with results compared against published manufacturer data. The report finally uses these findings to identify the most suitable materials for high performance and sustainable engineering applications.

2 Literature Review

2.1 Composite Materials Used in the Sector

Carbon-fibre reinforced polymer remains the main high-performance material where stiffness and low mass are critical, which explains its continued use in motorsport safety structures, crash attenuators and premium vehicle components (Zhang et al., 2023). In Formula 1, carbon became central because it enabled stiff survival cells and lightweight energy-absorbing structures that metals could not match at equal mass (Savage, 2010). Aluminium remains the most suitable benchmark because it is isotropic, mature and already established in transport manufacture (Miller et al., 2000). Flax composites occupy a narrower role in semi-structural parts because they offer low density, useful specific stiffness and damping, but they are not direct substitutes for carbon in the most stiffness-critical structures (Pickering, Efendy and Le, 2016). Kevlar is better treated as a toughness- and impact-oriented reinforcement than a maximum-stiffness material (Dharmavarapu and Sreekara Reddy, 2022).

2.2 Material Structure and Properties

Fibre type is the main driver of tensile response. Carbon provides the highest stiffness and strength, flax offers lower absolute properties but useful specific performance, and aramid provides moderate tensile capability with high toughness (Pickering, Efendy and Le, 2016; Dharmavarapu and Sreekara Reddy, 2022). Aluminium differs by providing predictable isotropic elasticity followed by plastic deformation (Miller et al., 2000). Reinforcement architecture then determines how efficiently these properties are translated into laminate behaviour. Woven laminates are generally more efficient than non-woven systems in axial tension because more fibre is aligned with the load, while non-wovens tend to show lower modulus, lower strength and greater scatter (Pickering, Efendy and Le, 2016). The matrix is less important for longitudinal stiffness, but remains important for wet-out, load transfer and damage resistance. Well-formulated bio-based epoxies can approach conventional epoxy performance in carbon twill laminates (Boursier Niutta et al., 2023).

2.3 Manufacturing Methods

Resin or vacuum infusion is the most relevant manufacturing route for the present specimen set because it suits dry textile reinforcements and is widely used in low-volume automotive and motorsport production (Wang et al., 2023). Laminate quality depends strongly on fibre volume fraction, void content and thickness uniformity, so manufacturing consistency directly affects tensile performance. Common defects include race-

tracking, dry spots, tow distortion, local permeability variation and resin-rich regions (Bodaghi et al., 2019). These effects are particularly important when comparing woven and non-woven materials, and are often more severe in natural-fibre and higher bio-content laminates.

2.4 Applications and Engineering Trade-Offs

Woven carbon/epoxy remains the strongest reference point for lightweight structural efficiency because it provides the best combination of tensile stiffness and strength at low mass (Zhang et al., 2023). Woven carbon/bio-resin is important because some of this performance may be retained while reducing reliance on a fully petrochemical matrix, although this depends on resin formulation and process quality (Boursier Niutta et al., 2023). Flax composites are less suitable for primary stiffness-critical structures, but remain attractive where damping, lower density and improved sustainability matter more than maximum tensile strength (Pickering, Efendy and Le, 2016). Kevlar woven bio-resin is more relevant to impact-tolerant or protective components than stiffness-dominated structures (Dharmavarapu and Sreekara Reddy, 2022). Overall, changing fibre type and architecture has a much larger mechanical effect than changing from conventional epoxy to a moderately bio-based epoxy.

3 Sustainability Analysis

Flax-based composites offered the strongest sustainability case at the resource-extraction stage because flax is renewable and generally has a lower climate burden than synthetic reinforcements (Deng and Tian, 2015). However, this benefit depends on cultivation conditions, transport distance and electricity mix (Fitzgerald et al., 2021). Carbon fibre and Kevlar remain dependent on petrochemical precursors and energy-intensive processing (Das, 2011). Aluminium also carries a high primary production burden, although this can be reduced substantially where secondary scrap replaces primary metal (Rossi et al., 2025). Bio-resin is therefore only a partial improvement, because it reduces fossil dependence without solving thermoset end-of-life limitations (La Rosa et al., 2014).

Manufacturing impact was dominated by fibre production rather than laminate lay-up alone. This was most significant for the carbon systems, where stabilisation and carbonisation made production far more energy intensive than flax-based alternatives (Das, 2011). This is relevant because the specimens were produced by resin infusion, which is suitable for low-volume motorsport and automotive composites but still requires energy, resin preparation and single-use consumables (Ramachandran, Gnanasagaran and Vekariya, 2023). Bio-resin may reduce impact slightly relative to conventional epoxy, but only incrementally when carbon fibre remains the reinforcement (La Rosa et al., 2014).

Recyclability and end-of-life performance clearly favoured aluminium because it can be repeatedly remelted within a mature industrial system (Rossi et al., 2025). Carbon-fibre thermosets had the most credible recycling routes among the composites, including mechanical recycling, pyrolysis and solvolysis, but true closed-loop reuse remained limited (Qureshi, 2022). Closed-loop CFRP recovery only offered clear benefit when recovered fibre displaced virgin material (Tapper et al., 2020). The flax and Kevlar bio-resin laminates were still constrained by their cured thermoset matrix, so natural fibre should not be confused with full biodegradability (Fitzgerald et al., 2021).

From a lifecycle perspective, fibre choice had a greater influence than weave architecture and often more influence than resin choice. Carbon woven epoxy was therefore the least favourable composite option because it combined the highest-burden reinforcement with a conventional fossil-derived matrix (Alrehaili, Nurdiawati and Al-Ghamdi, 2025). Carbon woven bio-resin and carbon non-woven bio-resin improved the matrix side of the footprint only partially, because carbon fibre remained the dominant hotspot (Das, 2011). Flax-based systems generally offered the lowest-impact composite

option, although more material might be required to meet a given mechanical target (Deng and Tian, 2015). Flax woven bio-resin was therefore a more credible low-impact option than flax non-woven bio-resin, while Kevlar woven bio-resin remained a specialist material rather than a sustainability leader (Alrehaili, Nurdawati and Al-Ghamdi, 2025).

Policy direction supported this ranking. The proposed European End-of-Life Vehicles Regulation favoured materials that could be identified, dismantled and recirculated, which directly benefited aluminium and increased pressure on thermoset composites to demonstrate viable recovery routes (European Commission, 2023). In motorsport, the pressure was more indirect, with FIA strategy focusing on carbon accounting and procurement rather than direct material bans (FIA, 2020).

Overall, flax woven bio-resin was the most sustainable composite option in the present material set, provided the duty cycle could be met without significant overdesign. Carbon woven epoxy was the least sustainable overall, while carbon woven bio-resin represented the best performance-sustainability compromise. Aluminium remained the most circular and industrially mature material overall, particularly where high recycled content and established recovery loops were available (Rossi et al., 2025).

4 Experimental Testing

4.1 Materials Tested

The materials evaluated comprise one metallic baseline and six composite systems. Aluminium was used as the reference material. The composites were carbon non-woven bio-resin, carbon woven bio-resin, carbon woven epoxy, flax non-woven bio-resin, flax woven bio-resin, and Kevlar woven bio-resin. This allowed comparison between conventional and lower-impact reinforcements, woven and non-woven architectures, and bio-resin and conventional epoxy systems.

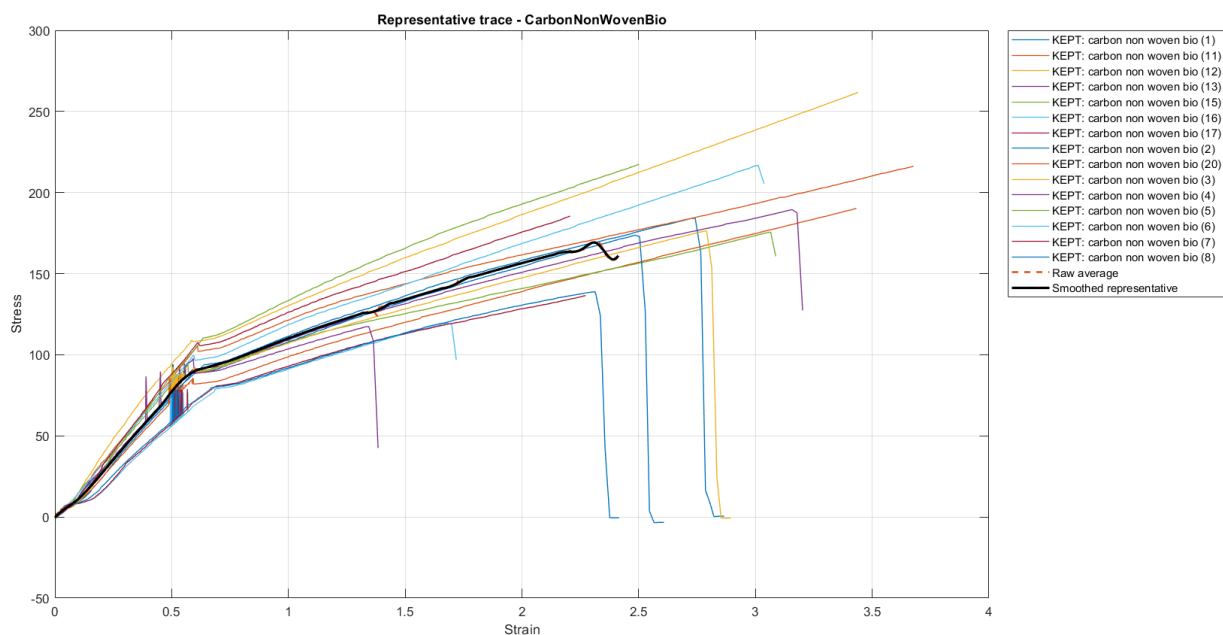


Figure 1 Carbon non-woven bio test results with smoothed average

4.2 Specimen Construction

The composite specimens were manufactured by resin infusion. Additional mesh was incorporated to improve grip during tensile testing, and the materials were sourced from Easy Composites. Woven twill laminates used three layers of 200g reinforcement, giving 600g total, while the non-woven materials used a single 300 g layer. Where multiple plies were used, they were arranged at 45° to one another. This lay-up was expected to influence tensile response compared with a fully aligned laminate. Carbon-based materials were assessed using the stated 50:50 fibre-volume fraction assumption, while the remaining systems used manufacturer data-sheet values.



Figure 2 Material samples prior to testing

4.3 Test Procedure

Tensile testing was carried out using the Denison tensile/compression machine in IQ007 under technician supervision. Each specimen was measured before test so that cross-sectional area could be calculated and used to convert load data into stress. The specimens were then loaded in uniaxial tension until failure, while load against time data was recorded. Two tests per group were completed for each material, contributing to a larger pooled class dataset of approximately twenty tests per material. The data was exported for later processing. Testing was completed in accordance with laboratory health and safety requirements, and unreliable files were excluded where advised by the technician.



Figure 3 Aluminium sample set up in the Dennison machine with the extensometer attached

4.4 Data Processing Method

The tensile data was organised into material folders and processed in MATLAB. The processing MATLAB script had originally been developed by Crockford, (2026), and was used as a data-handling tool prior to interpretation of the results. In this script, all stress-strain traces were plotted first, and invalid or inconsistent traces were removed before averaging. A single representative stress-strain curve was then produced for each material by aligning the retained traces to the origin, interpolating them onto a common grid, and averaging them. Young's modulus was taken from the early linear region, yield from the first clear departure from that response, ultimate tensile strength from the peak stress, and final strain from the final point on the representative curve.

5 Results

5.1 Representative Stress-Strain Curves

5.1.1 Aluminium

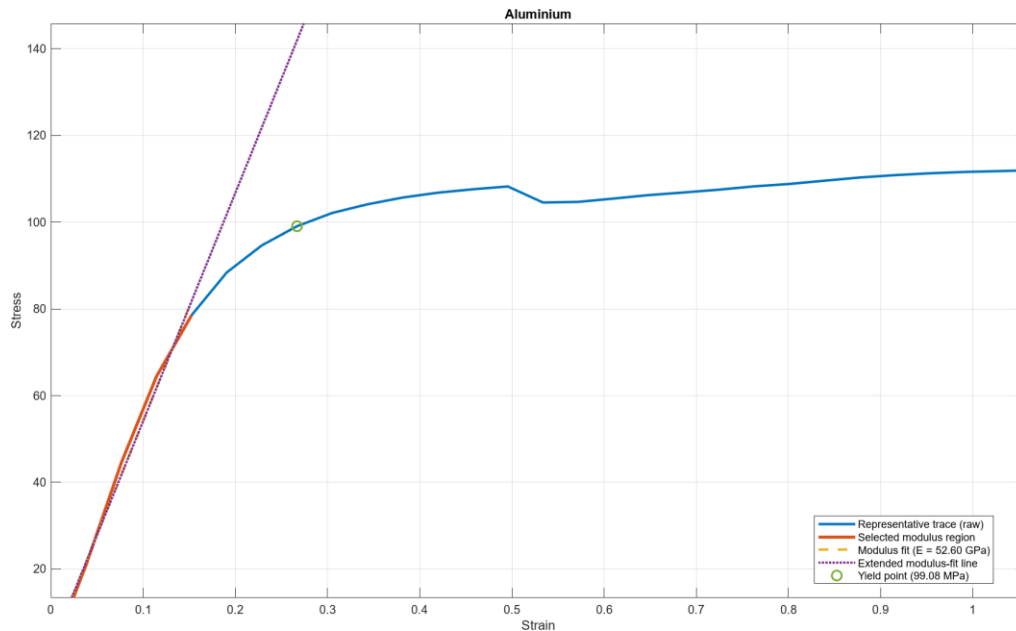


Figure 4 Aluminium Stress / Strain plot

The aluminium response showed a ductile metallic behaviour, with an initial linear region followed by yielding and continued plastic deformation over a large strain range. It therefore showed lower stiffness and strength than the strongest carbon laminates, but much greater strain to failure.

5.1.2 Carbon Non-Woven Bio

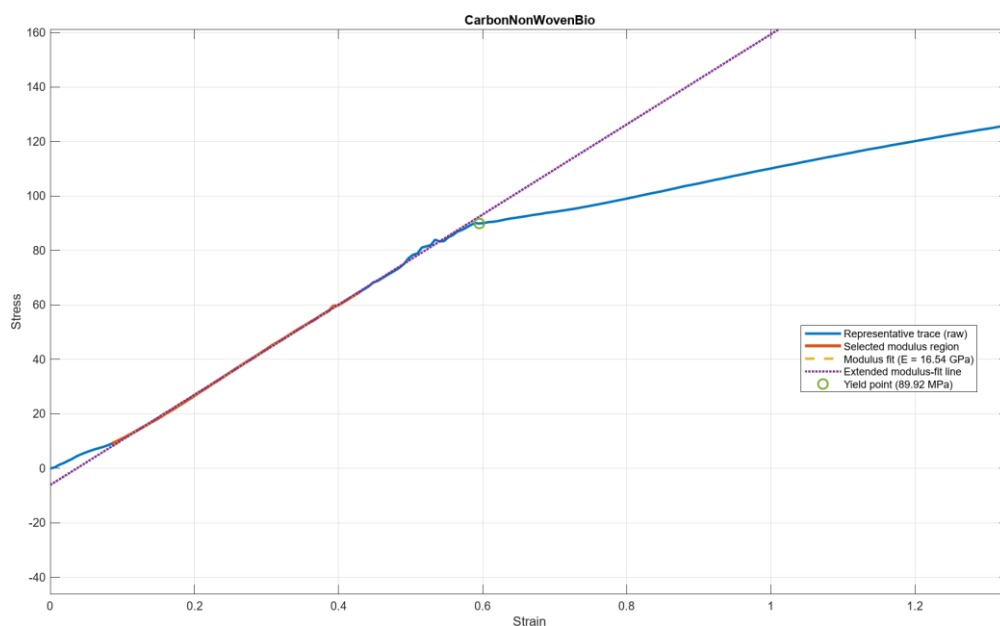


Figure 5 Carbon non-woven with bio resin stress / strain plot

Carbon non-woven bio showed an initial near-linear region followed by a more gradual transition away from linear behaviour than the woven carbon laminates. It continued to carry load over a modest strain range after yield, indicating a more progressive response, but it showed much lower stiffness and strength than the woven carbon systems.

5.1.3 Carbon Woven Bio

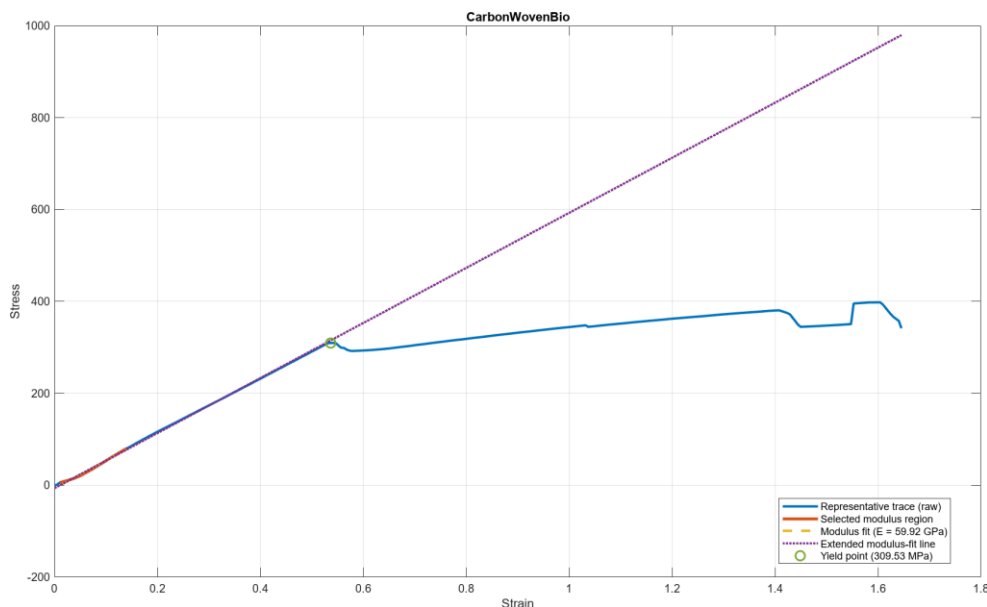


Figure 6 Carbon woven with bio resin stress / strain plot

Carbon woven bio showed a steep initial linear region, confirming high stiffness. Yield occurred at low strain and was followed by limited further deformation before failure. Based on the processed results, this material gave the highest ultimate tensile strength of all materials tested.

5.1.4 Carbon Woven Epoxy

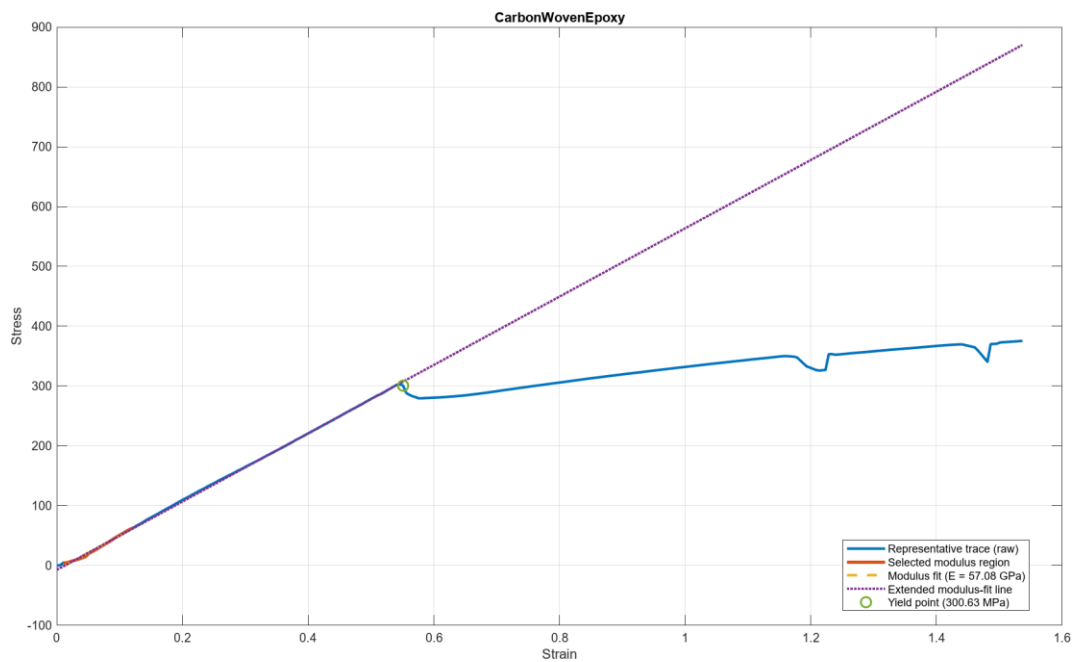


Figure 7 Carbon woven with epoxy stress / strain plot

Carbon woven epoxy showed a very similar steep initial linear response to carbon woven bio, confirming high stiffness and strength. It remained one of the strongest materials tested, although its modulus, yield stress and UTS were all slightly lower than those of carbon woven bio.

5.1.5 Flax Woven Bio

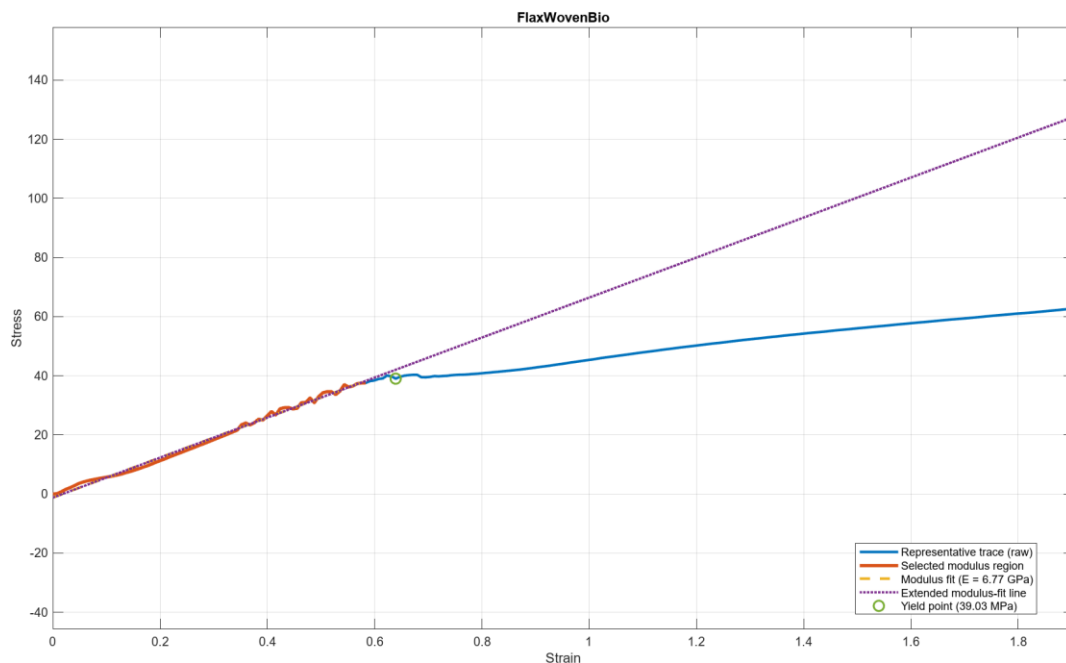


Figure 8 Flax woven with bio epoxy stress / strain plot

Flax woven bio showed a shallow initial slope and much lower stiffness than the carbon woven laminates and Kevlar laminate. The early region was less clearly defined, suggesting greater variability and reduced confidence in the modulus value. It remained mechanically weak, although it showed greater strain to failure than the woven carbon laminates.

5.1.6 Flax Non-Woven Bio

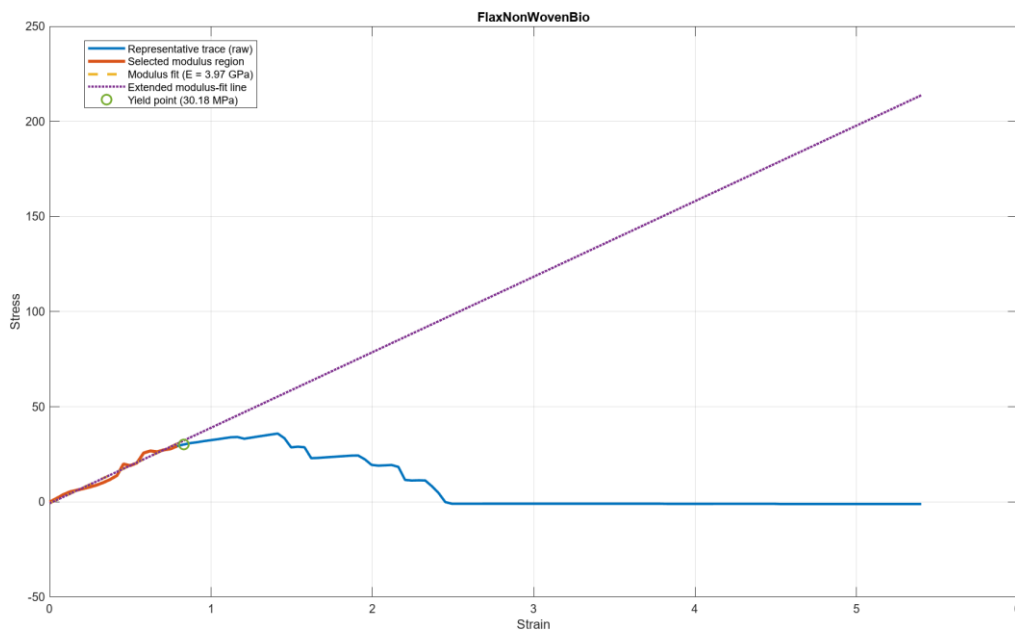


Figure 9 Flax non-woven with bio epoxy stress / strain plot

Flax non-woven bio showed the lowest stiffness and strength of all materials tested. Its early region was also less clearly linear than the carbon-based datasets, and after a relatively low peak stress it showed a pronounced loss of load-carrying capacity, indicating limited tensile performance.

5.1.7 Kevlar Woven Bio

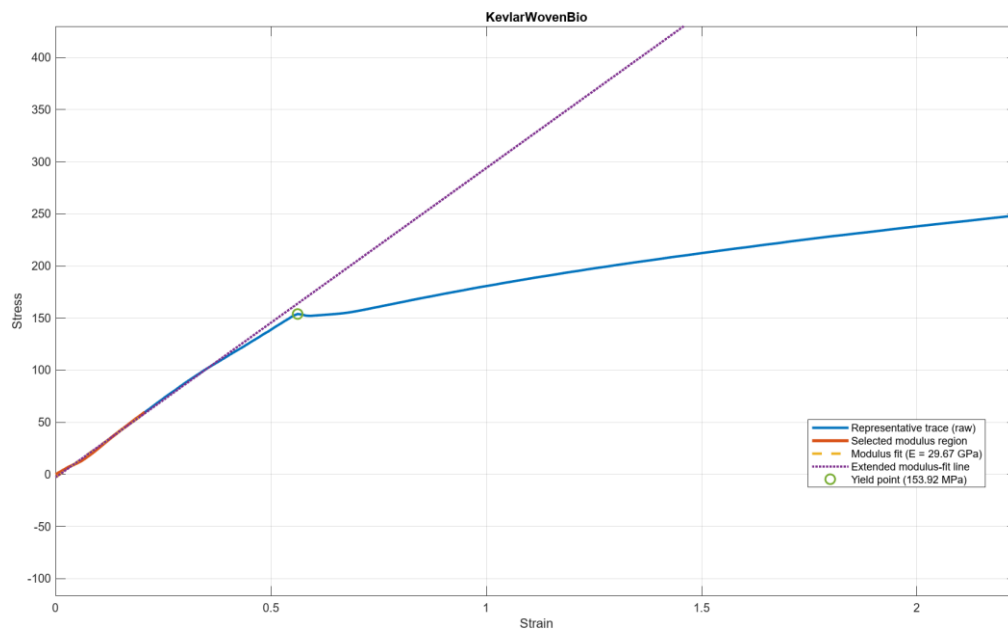


Figure 10 Kevlar woven with bio epoxy stress / strain plot

Kevlar woven bio showed an initially linear response followed by a more progressive post-yield region than the woven carbon laminates. It had lower stiffness and strength than woven carbon, but much greater strain to failure.

5.2 Summary of Material Properties

Table 1 material properties summary table

Material	Kept traces	Young's modulus, (GPa)	Yield stress, (MPa)	Yield strain (%)	UTS, (MPa)	UTS strain (%)	Final strain (%)
Aluminium	34	10.94	110.31	0.877	115.05	5.451	14.906
Carbon non-woven bio	15	11.06	114.62	1.087	169.24	2.308	2.413
Carbon woven bio	10	61.44	303.48	0.552	401.45	1.589	1.646
Carbon woven epoxy	14	58.72	288.28	0.556	376.18	1.527	1.537
Flax non-woven bio	12	3.97	31.95	0.956	34.78	1.247	5.401
Flax woven bio	10	6.77	39.52	0.687	87.78	3.890	3.890
Kevlar woven bio	9	30.42	152.43	0.601	320.36	4.198	4.238

Table 1 presents the mechanical properties extracted from Crockfords, (2026) MATLAB script. The table also includes the number of traces retained after filtering for each material set.

The processed results showed that the carbon woven materials produced the highest modulus and strength values, with carbon woven bio returning the highest ultimate tensile strength overall. In contrast, the flax-based materials produced the lowest modulus and strength values, although aluminium showed the greatest final strain to failure.

5.3 General Observations

Carbon woven bio produced the highest Young's modulus and ultimate tensile strength, with carbon woven epoxy close behind. Kevlar woven bio formed an intermediate case, showing good strength with a more progressive response than the woven carbon laminates. Aluminium showed by far the greatest final strain to failure, confirming its ductile behaviour. Carbon non-woven bio showed only a modest stiffness increase over aluminium but a higher ultimate tensile strength, while both flax-based materials produced the lowest modulus and strength values. The modulus extraction for aluminium, flax non-woven bio and flax woven bio was less reliable than for the other materials, so these stiffness values should be treated with more caution.

6 Validation Method

The experimental results were compared against manufacturer reference data where available. Table 2 compares the measured Young's modulus and ultimate tensile strength values against the published data. Where the manufacturer reported a range or directional values, a mean reference value was used to calculate a simple percentage correlation.

Table 2 experimental Vs published results

Material	Experimental modulus, (GPa)	Published modulus, (GPa)	Modulus correlation, (%)	Experimental UTS, (MPa)	Published tensile strength, (MPa)	UTS correlation, (%)	Source
Aluminium	10.94	71.00	15.4	115.05	125.00	92.0	Aalco
Carbon non-woven bio	11.06	30.00	36.9	169.24	310.00	54.6	Easy Composites
Carbon woven bio*	61.44	234.00	26.3	401.45	4120.00	9.7	Easy Composites
Carbon woven epoxy*	58.72	234.00	25.1	376.18	4120.00	9.1	Easy Composites
Flax non-woven bio	3.97	5.00	79.4	34.78	40.50	85.9	Eco-Technilin
Flax woven bio	6.77	6.50	104.2	87.78	59.50	147.5	Eco-Technilin
Kevlar woven bio*	30.42	112.40	27.1	320.36	3000.00	10.7	Easy Composites

(Aalco, 2026; Easy composites, 2026; Eco-Technilin, 2026)

For the woven carbon and Kevlar materials, the manufacturer mainly published dry reinforcement or fibre property data rather than cured laminate tensile properties. These values were therefore used only as broad reference data.

7 Discussion

7.1 Comparison with Aluminium Baseline

Aluminium showed the most ductile tensile response of all materials tested, with clear yielding followed by sustained plastic deformation over a large strain range. In contrast, the composite materials generally failed at much lower strain, indicating stiffer but less ductile behaviour. The carbon woven laminates clearly exceeded aluminium in both Young's modulus and tensile strength, but did not approach its strain to failure. Carbon non-woven bio offered only a modest strength increase over aluminium and showed a similar modulus, while still failing at a much lower strain. Kevlar woven bio also exceeded aluminium in both stiffness and strength, but retained a more progressive post-yield response than the carbon woven laminates. Overall, aluminium remained the best performer in terms of ductility, whereas the stronger composite systems provided improved stiffness and strength at the expense of deformation capacity.

7.2 Twill Versus Non-Woven Comparison

The woven laminates generally produced higher stiffness and strength than the non-woven materials, indicating that woven reinforcement provided a more efficient tensile load path. This was clearest in the carbon systems, where the woven laminates greatly exceeded carbon non-woven bio in both modulus and tensile strength, although the non-woven material showed a slightly more progressive post-yield response. A similar trend was observed in the flax materials, with flax woven bio performing better than flax non-woven bio. Overall, the results indicated that both reinforcement architecture and fibre type strongly influenced tensile behaviour.

7.3 Bio-Resin Versus Traditional Resin Comparison

Comparison of the woven carbon laminates showed only a small mechanical difference between the bio-resin and traditional epoxy systems. Carbon woven bio produced slightly higher modulus, yield stress and ultimate tensile strength values than carbon woven epoxy, but the overall curve shape was very similar. This suggests that, for the woven carbon specimens tested here, fibre type and architecture had a larger effect than the change from conventional epoxy to bio-resin. The bio-resin therefore did not introduce an obvious mechanical penalty in this material set.

7.4 Effect of 45 Degree Ply Orientation

The use of plies arranged at 45° was likely to influence tensile response. In a uniaxial test, such an off-axis lay-up would be expected to reduce direct longitudinal stiffness and strength compared with a more fully aligned laminate. However, several of the composite curves continued to carry load after the initial departure from linearity, suggesting progressive redistribution of load between plies. The 45° arrangement may therefore have reduced peak tensile performance, but also contributed to the less abrupt failure behaviour seen in some materials.

7.5 Failure Behaviour

The curve shapes suggested clear differences in failure behaviour between the material systems. The carbon woven laminates appeared to fail in a relatively abrupt and brittle manner after yielding, whereas Kevlar woven bio, flax woven bio and carbon non-woven bio showed a more progressive post-yield response. In contrast, flax non-woven bio exhibited a pronounced loss of load-carrying capacity after peak stress, indicating earlier structural breakdown. These differences suggest that the materials failed through different combinations of fibre fracture, matrix cracking, delamination and load redistribution.

7.6 Validation Against Literature and Manufacturer Data

Comparison with Table 2 showed mixed levels of agreement across the material set. The closest correlation was obtained for the flax-based materials, particularly flax non-woven bio and the modulus of flax woven bio. However, the tensile strength of flax woven bio exceeded the published mean value, suggesting either favourable specimen quality or variability between the supplied material and the reference dataset. Aluminium showed good agreement in tensile strength but very poor modulus correlation, suggesting that the selected benchmark was not fully representative or that modulus extraction was affected by the less clearly defined early linear region. The lowest correlations were observed for the woven carbon and Kevlar materials, but these values were based on dry reinforcement or fibre properties rather than cured laminate properties.

8 Recommendations

For applications in which maximum tensile performance is the primary requirement, carbon woven bio is recommended. It produced the highest Young's modulus and ultimate tensile strength, with

carbon woven epoxy performing similarly but slightly below it. From a sustainability perspective, the flax-based materials and bio-resin systems are more attractive, but their lower stiffness and strength would limit them to lightly loaded or non-critical components. On balance, carbon woven bio is recommended as the best overall compromise, because it delivered the highest measured tensile performance without an obvious mechanical penalty from the bio-resin. Kevlar woven bio may also be considered where greater deformation tolerance is required. Future work should include additional repeat testing, tighter control of specimen quality, and further lifecycle assessment supported by flexural, impact and fatigue testing.

9 Conclusion

This report evaluated the mechanical performance and sustainability of aluminium, carbon, flax and Kevlar-based material systems for potential use in automotive, motorsport and motorcycle engineering. The tensile results showed that the woven carbon laminates delivered the strongest overall mechanical performance, with carbon woven bio-resin producing the highest Young's modulus and ultimate tensile strength of the tested materials. Carbon woven epoxy performed similarly, but at a slightly lower level. Kevlar woven bio-resin provided lower stiffness and strength than the woven carbon systems, but showed greater deformation capacity and a more progressive post-yield response. The flax-based laminates produced the lowest modulus and strength values, although flax woven bio-resin remained more effective than flax non-woven bio-resin.

From a sustainability perspective, flax woven bio-resin offered the strongest overall composite option because of its renewable reinforcement and lower expected lifecycle burden. Carbon woven epoxy represented the least sustainable material because it combined the highest-burden reinforcement with a conventional thermoset matrix. Carbon woven bio-resin provided the best performance-sustainability compromise, as it retained carbon-fibre mechanical capability while introducing a modest sustainability improvement through resin substitution. Aluminium remained the most circular and industrially mature material overall, but not the most structurally efficient. It was therefore concluded that material selection should be driven by the required design function, with carbon woven bio-resin representing the most balanced option for high-performance applications where both tensile capability and sustainability must be considered.

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