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Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Automotive Materials & Sustainability

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2110674

26/04/26

Word Count: 2.998

(excluding tables, figures, references, citations and appendices)



Source: Arrangement of post-test samples (own image)

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1. Introduction

Composite materials are widely used in automotive and motorsport engineering because they can provide high strength and stiffness to weight ratios. However, material selection must also consider environmental impact, recyclability, manufacturing and service life. This report evaluates a range of composite materials through tensile testing and sustainability analysis. Woven and non-woven flax and carbon composites were compared with aluminium as a baseline material. The results were assessed against supplier data and published literature, alongside lifecycle impact, end-of-life limitations and policy pressures. The aim was to assess how well the tested materials balance mechanical performance with sustainability in automotive and motorsport use.

2. Literature Review

2.1 Composite materials and load transfer

Fibre-reinforced polymer composites combine a reinforcement, such as flax or carbon fibre, with a polymer matrix such as epoxy resin. These materials are used together to achieve a more useful balance of properties than either could provide alone. The matrix binds the fibres together, transfers load and helps protect fibres, while the reinforcement provides much of the strength and stiffness (Callister and Rethwisch, 2015). This differs from aluminium, which is more uniform in structure and behaviour and therefore provides a useful benchmark for comparison.

The relationship between matrix and reinforcement is central to understanding why the tested materials should behave differently. The mechanical response of a composite depends on the fibre properties, fibre content, the quality of the fibre/matrix interface, fibre dispersion, fibre orientation and manufacturing quality (Pickering, Efendy and Le, 2016). This is relevant because the tested materials include twill woven reinforcements and non-woven mats. Yan, Chouw and Jayaraman (2014) note that fibre configuration, manufacturing process, fibre volume and interface quality all influence the mechanical properties of flax fibre composites. These factors help explain why materials with similar fibre type may still behave quite differently in tensile testing.

2.2 Material systems selected for testing

Table 1 summarises the materials selected for testing and the basis for their comparison.

Table 1: Overview of materials used in testing, based on the supplied material datasheets and testing plan (Tudor, 2026; Easy Composites Ltd, 2024a–2024d; Easy Composites Ltd, 2025a; EcoTechnilin, 2023a; EcoTechnilin, 2023b).

Material	Composition	Form	Why included in study	Possible relevance to vehicle applications
Aluminium (baseline)	Single material aluminium	Flat metallic	Provides a familiar engineering benchmark against which the composite specimens can be compared.	Conventional reference material for automotive, motorsport applications.
Flax composites	Flax fibre with IB2 bio-epoxy resin	Twill woven fabric and non-woven mat	Represents a natural-fibre composite option with lower environmental impact and allows comparison between woven and non-woven samples.	More suited to lighter-duty parts where lower mass and lower environmental impact are desirable, such as trim, panels and other non-critical components
Recycled carbon composites	Recycled carbon fibre with IB2 bio-epoxy resin	Non-woven mat	Represents an attempt to retain useful carbon-fibre performance while improving sustainability through reclaimed fibre.	Relevant where higher performance than natural fibre is needed, but with better circularity than new carbon fibre
Carbon fibre composites	Carbon fibre with IB2 bio-epoxy resin and IN2 epoxy resin	Twill woven fabric	Allows comparison of high-performance composite behaviour and helps separate the effects of fibre type and resin choice.	Relevant to higher-performance lightweight parts in motorsport and automotive applications where stiffness and strength are priorities.
Kevlar woven composite	Aramid fibre with IB2 bio-epoxy resin	Woven fabric	To compare another high-performance synthetic reinforcement against carbon and flax.	Relevant where toughness and impact resistance are important.

Flax is one of the most widely used natural fibres in composite research and has attracted interest because of its renewable origin, low density and promising specific mechanical properties (Yan, Chouw and Jayaraman, 2014; Pickering, Efendy and Le, 2016). Yan, Chouw and Jayaraman (2014) note that flax fibres are cost-effective and can offer specific properties comparable to those of glass fibres, while flax composites made with a range of matrix types have shown promising mechanical performance. Pickering, Efendy and Le (2016) similarly identify natural-fibre composites as attractive because of their lower environmental impact, lower cost and potential across a wide range of applications. Barouni et al. (2022) also describe flax-based composites as one of the more promising natural-fibre systems, particularly where a more sustainable alternative to synthetic reinforcement is being sought. However, natural-fibre composites also have recognised limitations. Perremans et al. (2018)

point to issues including fibre/matrix compatibility, while Cuinat-Guerraz, Dumont and Hubert (2016) show that flax composites are sensitive to moisture. These limitations help explain why flax is not a direct substitute for carbon fibre in all applications.

Carbon fibre is strongly associated with high-performance automotive and motorsport use because of its high stiffness and strength to weight ratio. Pakdel et al. (2021) note that carbon fibre reinforced composites continue to play a key role in weight sensitive industries such as automotive engineering. The use of recycled carbon fibre is relevant because it aims to retain some of the performance advantages of carbon composites while reducing waste and reliance on new fibre production. The non-woven carbon mat used in the test programme is described as being made from 100% recycled carbon fibre and as suitable for both mould making and component manufacture (Easy Composites Ltd, 2024a).

2.3 Manufacturing routes and vehicle relevance

The manufacturing route is an important part of composite behaviour because final properties are influenced by factors such as fibre configuration, interface quality and the presence of voids within the laminate (Pickering, Efendy and Le, 2016; Yan, Chouw and Jayaraman, 2014). Resin choice is also important because it affects both processing and final properties. The IB2 bio-resin is presented as well suited to flax reinforcements and to resin infusion and Resin Transfer Moulding (RTM), while the IN2 resin is a more conventional high-performance infusion resin intended for structural parts and reinforcements such as carbon fibre (Easy Composites Ltd, 2024c; Easy Composites Ltd, 2024d).

These materials are relevant to automotive, motorsport and motorcycle applications because they value lightweight structures. Green composites are already used in interior and some exterior automotive parts, while flax composites offer potential where lower weight and sound absorption are beneficial (Koronis, Silva and Fontul, 2013; Dias et al., 2025; Yan, Chouw and Jayaraman, 2014). Taken together, the literature shows that the selected materials were sensible choices for testing and that differences in their tensile behaviour should be expected.

3. Methodology

3.1 Tensile testing procedure

Tensile testing was carried out using the Denison tensile/compression machine at UWTSD. Before testing, each sample was measured so that its cross-sectional area could be recorded. Each sample was then clamped between the machine grips and tightened before loading. An extensometer was used during the early part of the test to capture strain more accurately, then removed before final failure so the test could continue safely to fracture (Figure 1). This approach is consistent with standard tensile testing (Callister and Rethwisch, 2015).

3.2 Data processing and validation

The Denison output files were exported as CSV files and reviewed in Excel, while MATLAB was used to process and plot the stress–strain data. The files already included load, elongation, stress, strain, break stress and Young’s modulus. These values were based on the standard tensile relationships for engineering stress, engineering strain and modulus, with strain converted from percentage to decimal form (Appendix 1).

Results were screened, and any plots judged to be unreliable were excluded from the final analysis. This included plots with no clear failure event, plots with unusually shaped or excessively noisy curves, and plots with results far outside the range stated in the relevant supplier datasheets. The aim was to retain only results that gave a credible representation of the material response during tensile loading.

The final results were validated against supplier datasheets and published literature. A simple Law-of-mixtures calculation was considered only as a supporting check on stiffness trends, rather than as part of the main analysis (Appendix 2)

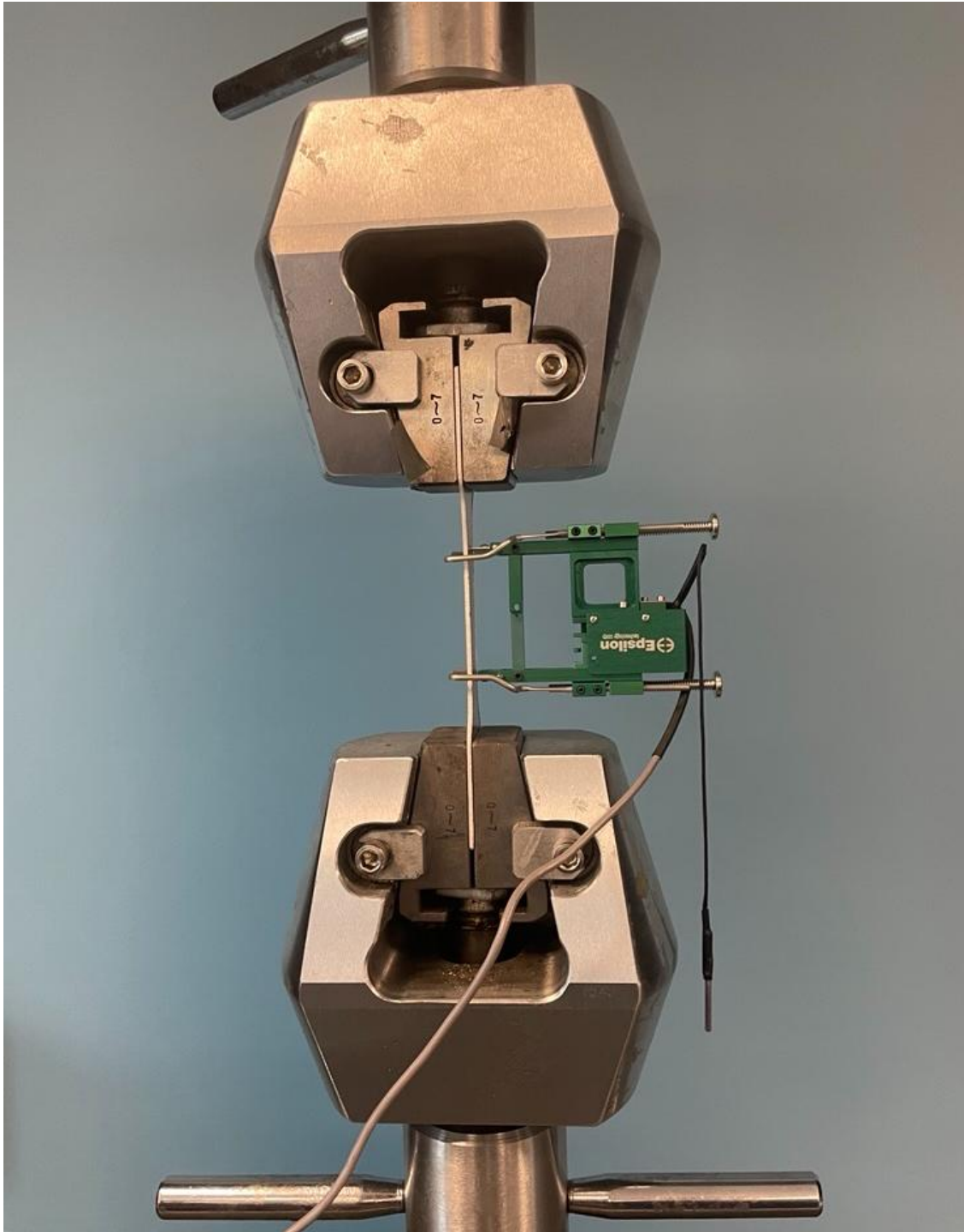


Figure 1: Tensile test setup showing the Denison test machine with the specimen clamped in the grips with the extensometer attached (own image).

4. Results and Analysis

This section presents the cleaned tensile dataset after unusable results were removed, focusing on baseline behaviour, reinforcement form, resin type and validation against reference data.

4.1 Overview of final tensile results

As shown in Table 2, the number of usable results was reduced across all groups after screening. Aluminium retained the largest valid dataset, whereas carbon woven bio and Kevlar woven bio had the lowest final sample counts, which should be considered when comparing mean values.

Table 2: Summary of test results used and rejected.

Material	Total No. of Test Results	No. of accepted test results	Tests which were rejected
Aluminium	38	33	21, 22, 28, 29, 30
Carbon non-woven bio resin	20	8	5, 6, 7, 9, 10, 11, 12, 14, 17, 18, 19, 20
Carbon woven bio resin	20	4	1, 2, 4, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20
Carbon woven epoxy resin	19	7	1, 2, 3, 4, 5, 6, 10, 12, 14, 15, 18, 19
Flax non-woven bio resin	21	8	1, 2, 3, 4, 5, 6, 7, 8, 10, 16, 19
Flax woven bio resin	19	9	2, 3, 6, 7, 8, 10, 11, 12, 18, 19
Kevlar woven bio resin	20	5	1, 4, 5, 6, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20

Table 3 shows clear differences in both tensile strength and stiffness between the material groups. The woven carbon materials gave the highest overall tensile performance, while the flax materials gave the lowest strength and stiffness. The standard deviations also show that consistency varied between materials. Aluminium and carbon woven epoxy gave relatively consistent results, whereas Kevlar woven bio and carbon woven bio showed much greater scatter. Flax woven bio modulus showed very little variation, so the low stiffness result was not just caused by one unusual test.

Table 3: Summary of mean tensile strength and stiffness by material with standard deviation.

Material	Mean UTS (MPa)	Standard Deviation of UTS (MPa)	Mean Modulus (GPa)	Standard Deviation of Modulus (GPa)
Aluminium	116.24	2.08	52.40	5.89
Carbon non-woven bio resin	159.50	29.45	9.12	6.11
Carbon woven bio resin	309.75	89.40	41.91	14.16
Carbon woven epoxy resin	420.71	30.41	57.92	7.08
Flax non-woven bio resin	45.50	6.46	4.91	3.72
Flax woven bio resin	86.78	9.26	1.71	0.27
Kevlar woven bio resin	414.40	180.71	18.43	12.09

4.2 Baseline comparison: aluminium vs composites

The representative curves in Figure 2 show that aluminium sustained much greater strain before failure than the carbon non-woven bio sample, indicating a more ductile response. Figure 3 shows the same overall pattern across the material set, with aluminium extending to much greater strain than the composite groups. This is consistent with the difference between ductile metallic behaviour and the more abrupt tensile failure commonly associated with fibre-reinforced composites (Callister and Rethwisch, 2015). The post-test samples in Figure 4 support this, with aluminium showing a more deformed fracture and the non-woven flax sample a cleaner break

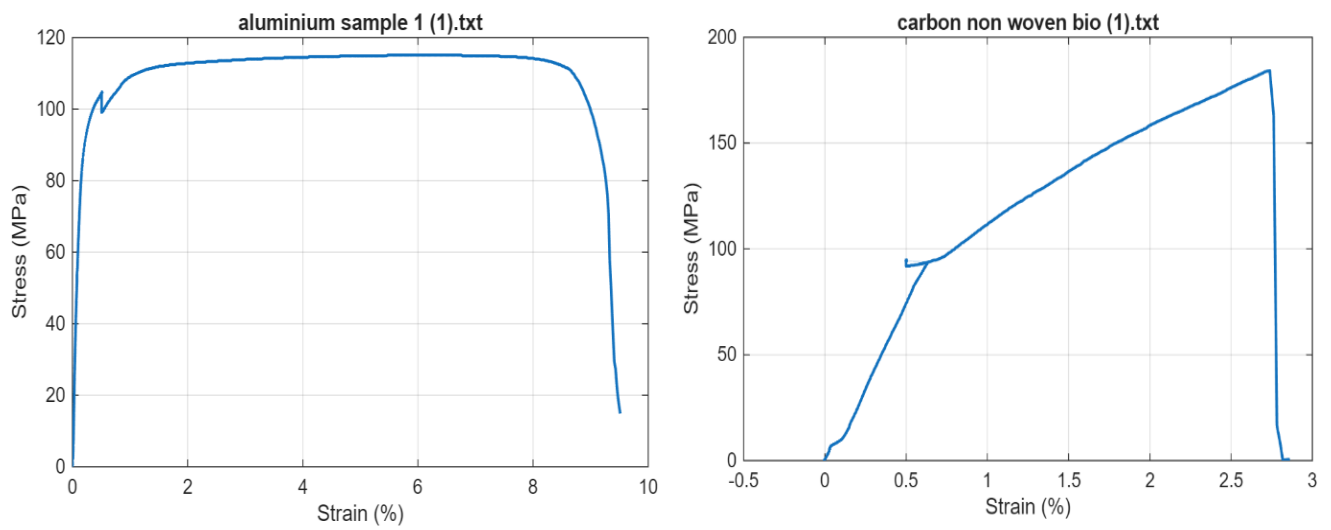


Figure 2: Representative tensile stress–strain curves for aluminium and carbon non-woven bio-resin samples.

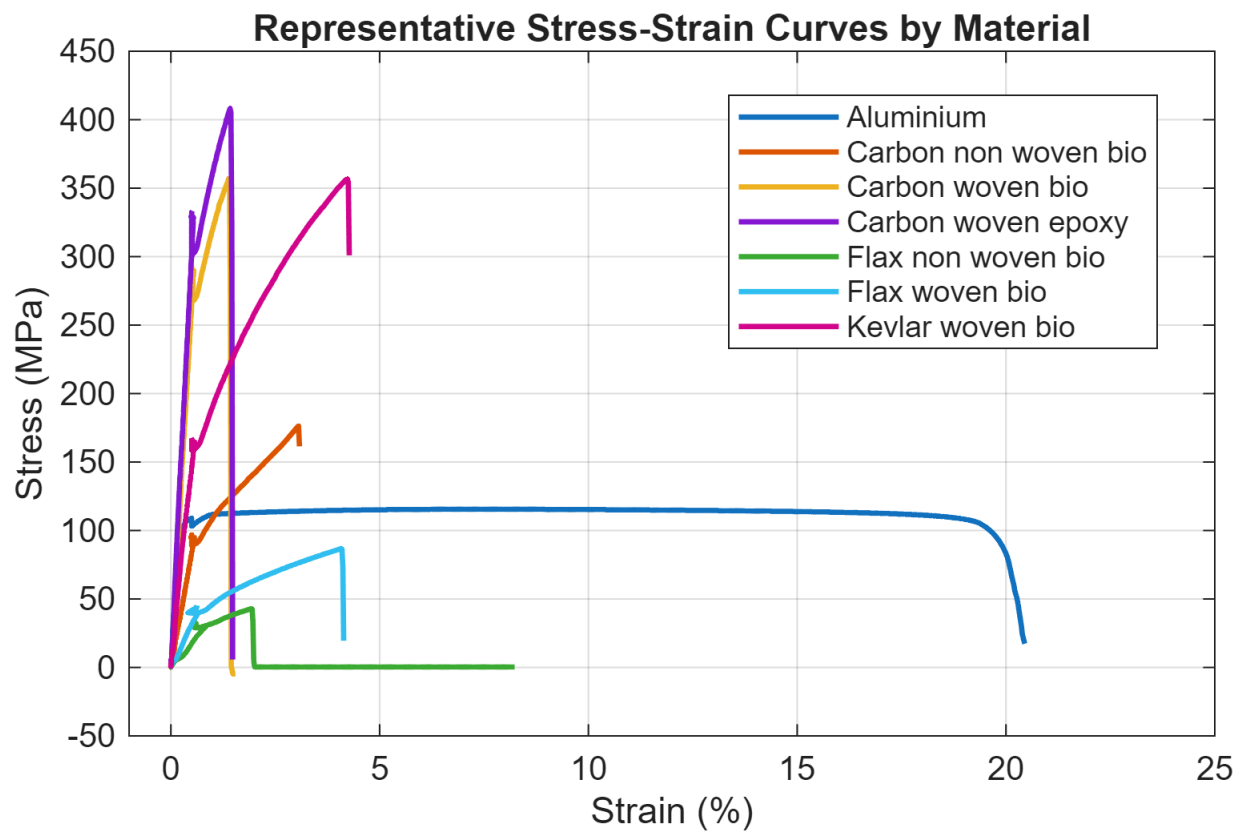


Figure 3: Representative stress–strain curves by material.

4.3

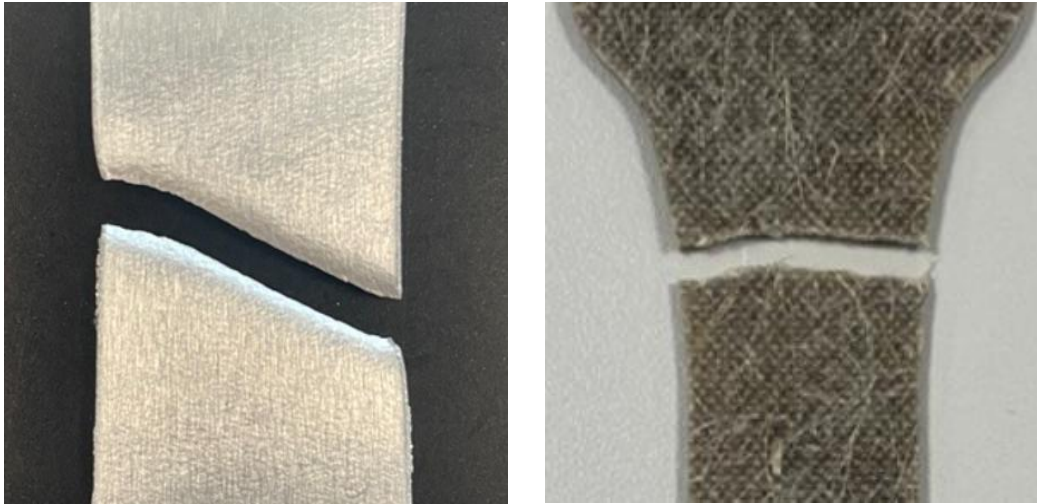


Figure 4: Comparison of post-test failure appearance for aluminium and non-woven flax composite samples (own image).

Effect of woven and non-woven reinforcement

Woven reinforcement increased UTS in both the flax and carbon groups. As shown in Figure 5 and Table 3, flax woven bio reached 86.8 MPa compared with 45.5 MPa for flax non-woven bio, while carbon woven bio reached 309.8 MPa compared with 159.5 MPa for carbon non-woven bio. This suggests that the woven forms were more effective in carrying tensile load than the corresponding non-woven mats.

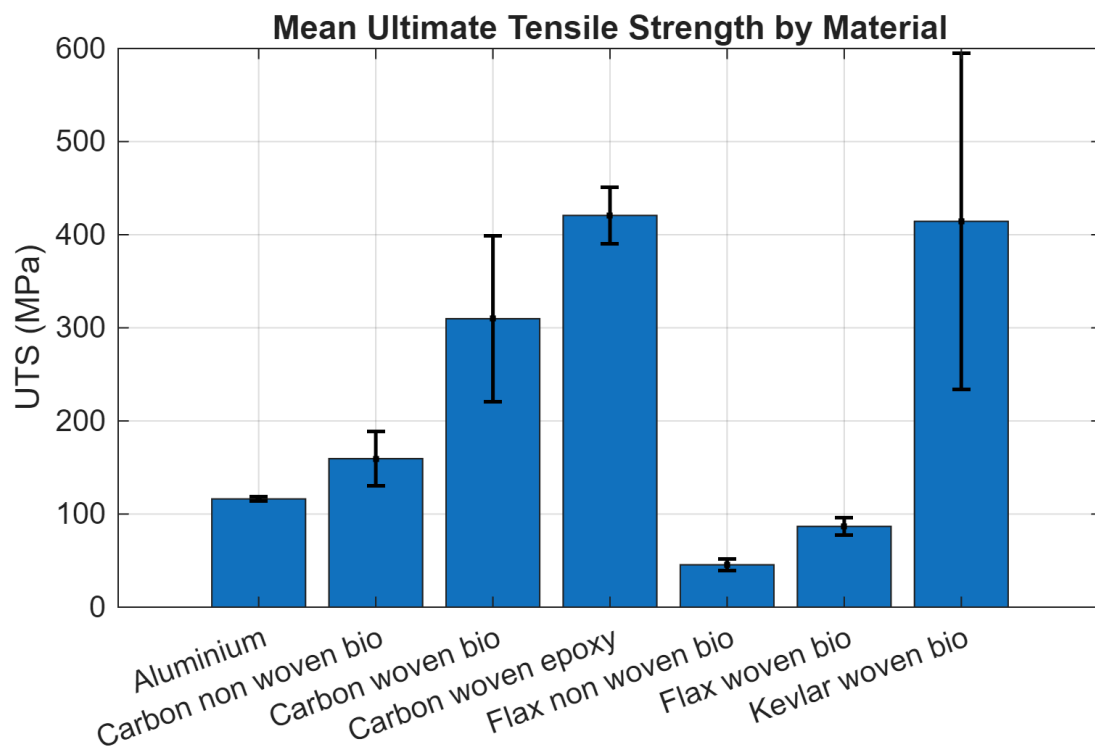


Figure 5: Mean ultimate tensile strength by material. Bars represent mean values and error bars represent standard deviation.

For modulus, the same trend was clear in the carbon group, where carbon woven bio reached 41.9 GPa compared with 9.1 GPa for carbon non-woven bio (Figure 6). In the flax group, however, the modulus result did not follow the same pattern. Flax non-woven bio gave 4.91 GPa, whereas flax woven bio gave only 1.71 GPa. This suggests that woven structure alone did not guarantee higher stiffness in the flax composite.

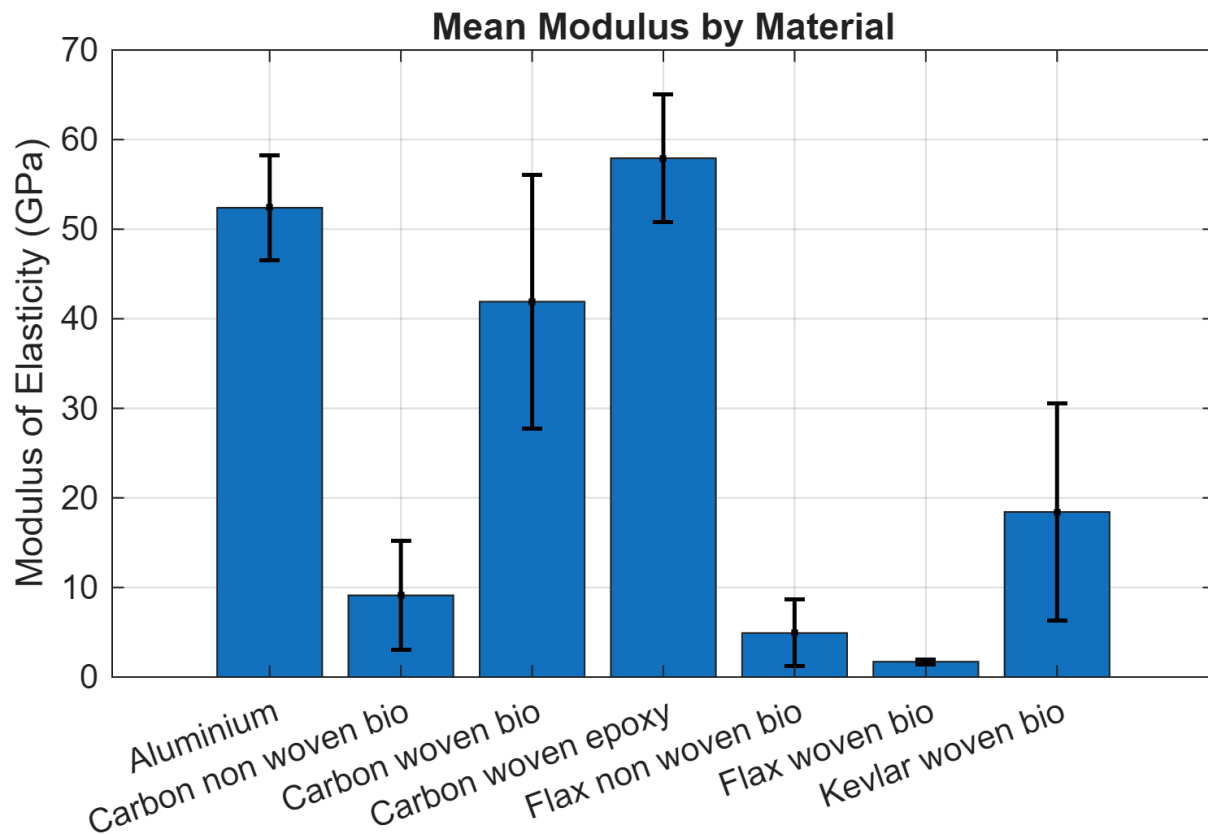


Figure 6: Mean modulus of elasticity by material. Bars represent mean values and error bars represent standard deviation.

Overall, the woven materials generally performed better in tension, but the benefit was much clearer in strength than in stiffness for the flax composites. This is consistent with the way fibre-reinforced composites behave, because their tensile response is strongly influenced by fibre direction, fibre content and how effectively the reinforcement carries load (Callister and Rethwisch, 2015). The 45° ply arrangement is also likely to have reduced the apparent stiffness of the woven laminates by loading some fibres off-axis.

4.4 Effect of resin type: bio-epoxy vs traditional epoxy

Carbon woven bio and carbon woven epoxy provided the only direct comparison between the two resin types. Carbon woven epoxy gave the higher mean UTS and modulus, with 420.7 MPa and 57.9 GPa respectively, compared with 309.8 MPa and 41.9 GPa for carbon woven bio (Table 3). This suggests that, within this dataset, the traditional epoxy resin produced the stronger and stiffer woven carbon material. Even so, carbon woven bio still performed strongly, indicating that the bio resin was also capable of supporting useful structural behaviour.

4.5 Validation against supplier and published data

The cleaned results were compared with the available supplier datasheets, as shown in Table 4. Direct comparison was possible for flax non-woven, flax woven and carbon non-woven materials. For woven carbon and Kevlar, the available datasheets should be treated only as approximate reference points because they do not describe directly comparable cured laminates.

As shown in Table 4, flax non-woven bio compared well with the directly relevant EcoTechnilin data. Flax woven bio showed a less consistent match, with UTS above the supplier range but modulus well below it. This could reflect the 45° arrangement and off-axis loading rather than calculation error. Carbon non-woven bio also fell below the published values, although this comparison is limited because the supplier states that the values are only approximate for a recycled material. Published literature also supports the greater variability seen in the flax groups, where fibre structure, interface quality and moisture sensitivity can influence tensile behaviour (Perremans et al., 2018; Cuinat-Guerraz, Dumont and Hubert, 2016).

Table 4: Summary of validation against supplier and published data.

Material	Testing mean UTS (MPa)	Supplier UTS (MPa)	Testing mean Modulus of Elasticity (GPa)	Supplier Modulus of Elasticity (GPa)	Validation Comment
Flax non-woven bio	45.5	44 ± 4 (CD) 37 ± 2 (MD)	4.91	5 ± 1	Good agreement with directly relevant supplier data.
Flax woven bio	86.6	58 ± 2 (weft), 61 ± 6 (warp)	1.71	6 ± 1, 7 ± 1	UTS was above the supplier range, but the modulus was much lower. The 45° ply arrangement may have reduced the stiffness measured in the test.
Carbon non-woven bio	159.5	330 (transverse), 290 (longitudinal)*	9.12	35, 25*	Both values were below the supplier data, although the comparison is limited because the published values are only approximate for a recycled material.
Carbon woven bio	309.8	443–644†	41.9	27.1–47.4†	Strength was below the closest woven-carbon reference, while the modulus was within the reference range. However, the comparison was only approximate because the reference material was not a direct match to the tested laminate.
Carbon woven epoxy	420.7	443–644†	57.9	27.1–47.4†	Strength close to closest woven-carbon reference, but not a direct material match.
Kevlar woven bio	414.4	3000‡	18.43	112.4‡	Reference values are for dry cloth reinforcement only, so not directly comparable with cured composite results.

Table notes

- CD = cross direction; MD = machine direction.
- * Carbon non-woven values are stated by the supplier to be approximate because the material is made from recycled carbon fibre of unknown origin.
- † High Strength Carbon Fibre Sheet values vary with orientation and thickness. The supplier gives tensile strength values from 443 to 644 MPa and tensile modulus values from 27.1 to 47.4 GPa for typical production sheets. These are the closest available woven-carbon mechanical values, but they are not a direct like-for-like match to the tested woven carbon samples.
- ‡ Kevlar values are for the woven cloth reinforcement itself, not for a cured composite made with resin. The datasheet gives tensile strength 3000 MPa and tensile modulus 112.4 GPa for the cloth.

4.6 Law of Mixtures

The law-of-mixtures check gave a theoretical modulus range of approximately 4.1–12.9 GPa for the woven flax/bio-resin (Easy Composites Ltd, 2024c; EcoTechnilin, 2023b; Perremans et al., 2018). The supplier datasheet modulus of 6–7 GPa lies within this range, whereas the experimental modulus of 1.71 GPa remained well below both the datasheet and theoretical values (Appendix 3). This suggests that the low measured stiffness is more likely to reflect the way the laminate was built and the test configuration. The woven laminate used plies arranged at 45°, which would be expected to reduce stiffness. Even so, the measured modulus remained unusually low relative to both theory and supplier data.

4.7 Variability, limitations and interpretation

Overall, woven reinforcement generally improved tensile performance relative to the non-woven mats, although the stiffness benefit was much clearer in carbon than in flax. Some limitations remain in the cleaned results. Final sample counts were low for some groups, particularly carbon woven bio and Kevlar woven bio, so those averages should be treated cautiously. Scatter was also high in Kevlar woven bio, making it harder to define a typical value for that group. Overall, the tensile strength results appear more reliable than some of the modulus values, particularly for flax woven bio.

5. Sustainability Analysis

5.1 Lifecycle and environmental impact

The environmental impact of a composite depends on its raw material origin, manufacturing route, service life and disposal method. The sustainability of the composites tested should therefore be judged across the whole lifecycle rather than only by their mechanical performance.

From a raw-material perspective, the clearest sustainability advantage lies with the flax composites. The supplied flax fibre materials are described as being intended for parts with a low environmental footprint, while the IB2 bio-resin is presented as a lower-impact alternative because part of its chemistry is derived from renewable plant-based glycerol and the mixed resin contains around 31% plant-based content (EcoTechnilin, 2023a; EcoTechnilin, 2023b; Easy Composites Ltd, 2024c). The IN2 resin is a conventional high-performance epoxy resin and does not make the same environmental claims (Easy Composites Ltd, 2024d). This makes the flax and bio-resin combination the most sustainable option in the current material set.

Natural fibres are not impact-free, but their carbon footprint can still be lower than that of carbon fibre composites. Ramachandran, Gnanasagaran and Vekariya (2023) reported a much lower global warming potential for a biocomposite than for a carbon fibre composite, which is consistent with wider literature on natural fibres and the high energy demand of virgin carbon fibre production (Perremans et al., 2018; Pakdel et al., 2021).

Manufacturing must also be considered, because a lower-impact raw material does not automatically result in a more sustainable final part. The samples were produced by resin infusion (Tudor, 2026). This is a controlled manufacturing method that still depends on chemical resins and curing processes and may also require additional energy input depending on the cure cycle used (Easy Composites Ltd, 2024c; Easy Composites Ltd, 2024d).

Service life is also important in lifecycle assessment. A lower-impact material that fails early or needs frequent replacement may not be the most sustainable option overall. This is particularly relevant for flax composites, which are sensitive to moisture absorption and can show reduced stiffness and altered failure behaviour over time (Cuinat-Guerraz, Dumont and Hubert, 2016). Natural fibre composites can also suffer from fibre/matrix compatibility issues

and variable mechanical behaviour (Perremans et al., 2018). This suggests that flax composites are better suited to lightly to moderately loaded parts rather than to the most demanding structural applications.

5.2 Recyclability and end-of-life

Recyclability and end-of-life remain significant weaknesses of composite materials because they combine different materials in one part, which are difficult to separate after manufacture. Callister and Rethwisch (2015) note this as a general recycling problem for composites, while Koronis, Silva and Fontul (2013) make the same point for conventional epoxy-based composite products.

The recycling literature shows that carbon fibre recycling is feasible but still limited. Pakdel et al. (2021) review mechanical, thermal and chemical recycling methods and conclude that fibre quality, surface condition, cost and process efficiency remain significant barriers. Recycled carbon fibre is often reused in lower-value or non-structural applications, so a true cradle-to-cradle loop has not yet been consistently achieved. Obunai and Okubo (2024) also show that reclaimed carbon fibre can be reused in remanufactured composites, and that improved reclamation conditions can reduce the loss of strength and toughness. This suggests that recycling routes are improving, but their practical use is still constrained by cost, process complexity and variable output quality.

This is directly relevant to this assignment because the supplied non-woven carbon mat is made from 100% recycled carbon fibre and is promoted as offering environmental and cost-saving advantages (Easy Composites Ltd, 2024a). Flax composites present a different end-of-life case. Although the fibre itself is renewable and may offer better energy recovery potential than synthetic fibres (Koronis, Silva and Fontul, 2013), the finished composite parts still rely on polymer resins and should therefore not be considered fully biodegradable (Cuinat-Guerraz, Dumont and Hubert, 2016). It is therefore more accurate to describe flax composites as lower-impact materials rather than fully circular end-of-life solutions.

5.3 Legislation, policy and governing bodies

Material selection is increasingly influenced by policy as well as engineering requirements. Koronis, Silva and Fontul (2013) link green composite development to the EU End of Life Vehicles Directive (Directive 2000/53/EC), which places pressure on vehicle design to improve reuse, recovery and recyclability.

In motorsport, a similar direction can be seen in governing-body strategy. The FIA Environmental Strategy 2020–2030 sets targets linked to carbon neutrality, net zero, reduced emissions and environmental action across championships and activities (FIA, 2020). The FIM Environmental Code is especially relevant in motorcycle engineering because it commits the organisation to a sustainability programme, compliance with environmental legislation, support for alternative energies and a more circular approach to product life cycles (FIM, 2024). Motorsport UK follows a similar approach by linking future motorsport development to climate action, resource efficiency and sustainable sourcing (Motorsport UK, 2021). Together, these documents show that motorsport policy is increasingly focused on carbon impact, resource efficiency and environmental management, which is likely to influence future material selection alongside normal engineering requirements.

5.4 Carbon-footprint reduction and practical implications

The clearest opportunity for reducing carbon footprint lies in using lower-impact composites where performance demands allow it. In this assignment, the flax and bio-resin combination appears to offer the lowest overall environmental impact (Ramachandran, Gnanasagaran and Vekariya, 2023). However, carbon-footprint reduction cannot be considered separately from engineering performance. In practice, this points towards a selective approach: flax composites where their performance is sufficient, and recycled carbon fibre where higher performance is still needed (Easy Composites Ltd, 2024a; Obunai and Okubo, 2024). Natural-fibre composites are also beginning to appear in motorsport and motorcycle applications, with recent industry examples showing flax-based bodywork being explored in motorcycle racing (Figure 7) (Bcomp, 2025).



Figure 7: Example of flax-based composite bodywork being explored for use in motorcycle racing (Source: Bcomp, 2025).

For higher-demand parts, recycled carbon fibre offers a more practical compromise. The supplied recycled non-woven mat and the wider recycling literature suggest that reclaimed fibre can reduce environmental impact while still retaining useful mechanical performance (Easy Composites Ltd, 2024a; Pakdel et al., 2021; Obunai and Okubo, 2024). Overall, sustainability appears to improve when flax and bio-resin are used where performance demands are moderate, while recycled carbon fibre is used where higher performance is still required. New carbon fibre made from raw materials remains the least attractive lifecycle option but may still be justified where no lower-impact alternative can provide equivalent performance (Ramachandran, Gnanasagaran and Vekariya, 2023; Pakdel et al., 2021).

6. Recommendations and Conclusion

The results of this study show that no single material is the best option for every application. Woven carbon with traditional epoxy gave the highest tensile performance and remains the most suitable choice for demanding structural parts. However, it also has the weakest sustainability case in the material set. Flax with bio-resin offered the strongest overall environmental case, but its lower tensile performance and greater sensitivity to moisture mean it is better suited to lightly or moderately loaded parts such as fairings and other non-critical components. Recycled carbon fibre provides the most balanced compromise where improved performance is needed with lower lifecycle impact than carbon fibre made from new raw material. Overall, the findings support a selective material strategy rather than a single best material conclusion. Further work should increase sample numbers and investigate moisture effects and fatigue behaviour to improve confidence in the results and explore better performance–sustainability trade-offs.

A further recommendation is to improve recycling and remanufacturing routes for composite materials, particularly carbon-fibre systems. Current methods are still limited by cost, process complexity and variable output quality. However, the literature shows that reclaimed carbon fibre can retain useful mechanical performance when reclamation is well controlled. The recycled carbon non-woven material used in this study suggests that improved recycling routes could make a meaningful contribution to reducing lifecycle impact, and continued pressure from governments and governing bodies is likely to help drive innovation in this area.

Composite components should also be designed with end-of-life in mind from the outset. This includes reducing unnecessary material complexity and favouring material systems that are easier to separate, recover or recycle where performance allows. Such an approach would better align composite design with lifecycle assessment principles and with the increasing regulatory focus on reuse, recovery and recyclability.

7. References

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8. Appendices

Appendix 1: Stress, Strain & Young's Modulus Calculations

For engineering stress, the standard relationship is

$$\sigma = \frac{F}{A}$$

Equation 1: Stress

where F is the applied load and A is the cross-sectional area of the sample.

For strain, the standard relationship is:

$$\varepsilon = \frac{\Delta L}{L}$$

Equation 2: Strain

where ΔL is the change in length and L is the original length of the sample (Callister and Rethwisch, 2015).

The modulus of elasticity is obtained from the slope of the initial linear part of the stress-strain curve,

$$E = \frac{\Delta \sigma}{\Delta \varepsilon}$$

Equation 3: Young's Modulus

(Callister and Rethwisch, 2015).

Strain values were expressed as percentages and so were converted to decimal form by dividing by 100 (Callister and Rethwisch, 2015).

Appendix 2: Law of Mixtures Calculation

The law of mixtures is a simple predictive approach used to estimate a property such as stiffness from the properties and volume fractions of the constituent materials, typically the fibres and the matrix (Callister and Rethwisch, 2015).

$$E_{cl} = E_m V_m + E_f V_f$$

Equation 4: Law of mixtures (upper-bound longitudinal modulus)

Where:

E_{cl} = modulus of elasticity of composite in the longitudinal direction

E_m = modulus of elasticity of the matrix

V_m = modulus of elasticity of the fibre

E_f = matrix volume fraction

V_f = fibre volume fraction

Appendix 3: Law of Mixtures – worked example

For a continuous aligned fibre composite, the upper-bound longitudinal modulus is:

$$E_{cL} = E_m V_m + E_f V_f$$

and the lower-bound transverse modulus is:

$$E_{cT} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

Equation 5: Law of Mixtures (lower-bound transverse modulus)

These are the standard rule-of-mixtures expressions given for fibrous composites (Callister and Rethwisch, 2015).

For the woven flax / bio-resin system, the values used were:

- resin modulus, $E_m = 3.04\text{GPa}$ (Easy Composites Ltd, 2024c)
- fibre volume fraction, $V_f = 0.29$ (EcoTechnilin, 2023b)
- matrix volume fraction, $V_m = 1 - V_f = 0.71$
- flax fibre modulus, $E_f = 30$ to 37GPa from Perremans et al., 2018 for technical flax fibres

1. Upper-bound longitudinal modulus

Using the lower flax-fibre modulus first:

$$\begin{aligned} E_{cL} &= E_m V_m + E_f V_f \\ E_{cL} &= (3.04 \times 0.71) + (30 \times 0.29) \\ E_{cL} &= 2.1584 + 8.7000 \\ E_{cL} &= 10.8584 \text{ GPa} \end{aligned}$$

So, the upper-bound longitudinal modulus using $E_f = 30\text{GPa}$ is:

$$E_{cL} \approx 10.86 \text{ GPa}$$

Using the upper flax-fibre modulus:

$$\begin{aligned} E_{cL} &= (3.04 \times 0.71) + (37 \times 0.29) \\ E_{cL} &= 2.1584 + 10.7300 \\ E_{cL} &= 12.8884 \text{ GPa} \end{aligned}$$

So, the upper-bound longitudinal modulus using $E_f = 37\text{GPa}$ is:

$$E_{cL} = 12.89 \text{ GPa}$$

That gives an upper-bound range of about 10.86–12.89 GPa.

2. Lower-bound transverse modulus

Using $E_f = 30\text{GPa}$:

$$\begin{aligned} E_{cT} &= \frac{E_m E_f}{V_m E_f + V_f E_m} \\ E_{cT} &= \frac{(3.04)(30)}{(0.71 \times 30) + (0.29 \times 3.04)} \\ E_{cT} &= \frac{91.2}{21.3 + 0.8816} \\ E_{cT} &= \frac{91.2}{22.1816} \\ E_{cT} &= 4.11 \text{ GPa} \end{aligned}$$

Using $E_f = 37\text{GPa}$:

$$\begin{aligned} E_{cT} &= \frac{(3.04)(37)}{(0.71 \times 37) + (0.29 \times 3.04)} \\ E_{cT} &= \frac{112.48}{26.27 + 0.8816} \\ E_{cT} &= \frac{112.48}{27.1516} \\ E_{cT} &= 4.14 \text{ GPa} \end{aligned}$$

Therefore, the lower-bound transverse modulus is about 4.11–4.14 GPa.

From those two calculations, the simple law-of-mixtures stiffness range for the woven flax / bio-resin system is 4.1 to 12.9 GPa.

The woven flax datasheet gives a modulus of 6–7 GPa, which sits inside that range (EcoTechnilin, 2023b).