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Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Automotive Materials & Sustainability (ACHA6012)

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1 Introduction

As an increasingly popular material option in the automotive, motorsport and motorcycle sectors, composites offer high strength-to-weight ratios, design flexibility and strong performance in lightweight structural and non-structural applications. These advantages are particularly valuable in industries focused on mass reduction, stiffness and mechanical efficiency. However, with increasing environmental concern, composite selection can no longer be assessed on these performance criteria alone. Environmental impact, end-of-life (EoL) management and recyclability are becoming increasingly important factors in modern engineering.

This shift means suitable materials must be evaluated using both technical and sustainability criteria. For the automotive, motorsport and motorcycle sectors specifically, these criteria are increasingly important due to legislative and competitive pressure to improve efficiency and performance while reducing the environmental cost of material systems. Therefore, determining the most appropriate material route requires each composite system to be assessed against both performance requirements and wider lifecycle implications.

This report examines a range of composite materials alongside an aluminium baseline through literature review, experimental testing and sustainability analysis. Mechanical response of each tested material is considered in tandem with published data and manufacturer data, before lifecycle implications are assessed in relation to resource use, manufacturing, recyclability, and EoL management. The findings are then used to inform recommendations regarding suitable material routes for future applications across the relevant industries.

2 Literature Review

Material selection for automotive, motorsport and motorcycle applications should not be based on a single material property, but rather the relationship between performance requirements, processing route, manufacturing feasibility and environmental impact. Ashby and Jones (2012) emphasise that material selection is most effective when properties are matched with functional demands of the component, rather than assessed in isolation. This is particularly relevant for lightweight vehicle structures, where strength, stiffness, density, durability and lifecycle impact all influence material suitability.

Carbon fibre reinforced polymers (CFRP) remain a key benchmark in high-performance vehicle applications because they combine low density with high specific strength and stiffness. Their mechanical response can also be tailored through fibre orientation, weave architecture, matrix selection and laminate design. This makes CFRP suitable for structural and semi-structural components where mass reduction and stiffness are important. However, the performance of CFRP is strongly dependent on reinforcement architecture and fibre–matrix load transfer (Callister Jr and Rethwisch 2020). As a result, woven, aligned and non-woven systems can produce substantially different mechanical behaviour even when reinforcement material is similar (Faulstich De Paiva et al. 2006).

Alongside conventional CFRP systems, environmental pressure has encouraged greater interest in natural-fibre reinforced polymers (NFRP), recycled reinforcements and bio-based resin systems. Flax is one of the most widely studied natural fibres because of its renewability, low density and potential for reduced embodied impact compared with synthetic fibres (Yan et al. 2014; Eleutério et al. 2025). However, its wider use in demanding structural applications remains limited by fibre-property variability, moisture uptake, fibre–matrix bonding and long-term durability concerns (Yan et al. 2014; Alajmi et al. 2022). These limitations mean flax-based composites are not direct replacements for CFRP, even where they offer environmental advantages.

Bio-based resins and recycled carbon reinforcements offer another route to reducing composite environmental impact without fully abandoning carbon fibre. Matrix substitution may reduce reliance on petrochemical resin systems, while recycled or non-woven carbon reinforcements can reduce dependence on virgin fibre production (Tapper et al. 2020; Easy Composites Ltd. 2024). However, these routes must be assessed against mechanical performance, since lower fibre alignment or weaker fibre–matrix bonding can reduce structural efficiency (Faulstich De Paiva et al. 2006; Callister Jr and Rethwisch 2020).

The selected materials therefore provide a useful engineering comparison rather than a simple sustainability contrast. Aluminium acts as a conventional lightweight metallic benchmark, woven CFRP in epoxy provides an established high-performance composite benchmark, woven CFRP in bio-resin assesses matrix substitution, non-woven CFRP highlights the influence of recycled reinforcement without a set orientation, and flax in bio-resin represents a complete NFRP alternative. This comparison supports the wider aim of the report by linking material structure, tensile performance and sustainability potential within a relevant vehicle-engineering context (Ashby and Jones 2012; Callister Jr and Rethwisch 2020).

3 Testing Methodology

Testing was conducted across 10 groups according to the provided testing plan, with additional prior test data used to assess different extension rates and material variations. Testing was conducted across five main material groups: aluminium, woven CFRP in epoxy, woven CFRP in bio-resin, non-woven CFRP, and woven flax fibre reinforced polymer (FRP), with later groups adding non-woven flax, Kevlar along and separate testing providing further results for analysis into different extension rates and material variations.

The purpose of tests was to compare mechanical response of selected materials under controlled conditions, providing a direct assessment of strength and stiffness behaviour for both metallic and composite materials (Callister Jr and Rethwisch 2020). All testing was carried out using the university Denison tensile testing machine with dog bone specimens (see Figure 1). An extensometer was connected to the gauge section, as shown in Figure 2, allowing strain to be measured more accurately during testing.



Figure 1: Denison tensile testing machine and dog-bone specimens used for material testing.



Figure 2: Extensometer connected to gauge section dog bone specimen in during tensile testing.

Recorded load–extension data was converted to stress–strain using specimen dimensions, allowing results from each material to be compared on a more normalised basis. This is particularly important for the composite samples where the behaviour is heavily dependent on the fibre-matrix architecture and manufacturing quality (Callister Jr and Rethwisch 2020; Alajmi et al. 2022). Results were then utilised in comparison to published data for similar material systems, with further validation acting as a comparison of trends rather than exact results due to variability known in composite performance (Faulstich De Paiva et al. 2006).

4 Experimental Results

Testing was conducted across numerous groups; however, the results presented primarily use Group 2 data to maintain consistency across the material comparison. Wider group results and prior testing were used where appropriate to support trend validation and assess variability. The key outputs considered were peak tensile stress, stress–strain response, Young’s modulus, failure strain and comparison with theoretical bounds calculated using the law of mixtures. This follows the testing guidance by using measured specimen dimensions, load data, twill versus non-woven structures, resin types and law of mixtures validation.

The mean peak tensile stress results in Figure 3 show clear separation between materials. Woven CFRP in epoxy produced the highest peak stress at 412 MPa, followed by woven CFRP in bio-resin at 372.91 MPa, indicating only a moderate reduction after matrix substitution. Non-woven CFRP showed lower peak stress due to its lack of aligned filaments but remains relevant because it uses 100% recycled fibres with bio-resin (Easy Composites Ltd. 2024). Aluminium and flax FRP were significantly lower at 115.25 MPa and 76.50 MPa respectively. Overall, the trend supports composite theory, where fibre orientation and reinforcement architecture strongly influence tensile load transfer (Callister Jr and Rethwisch 2020).

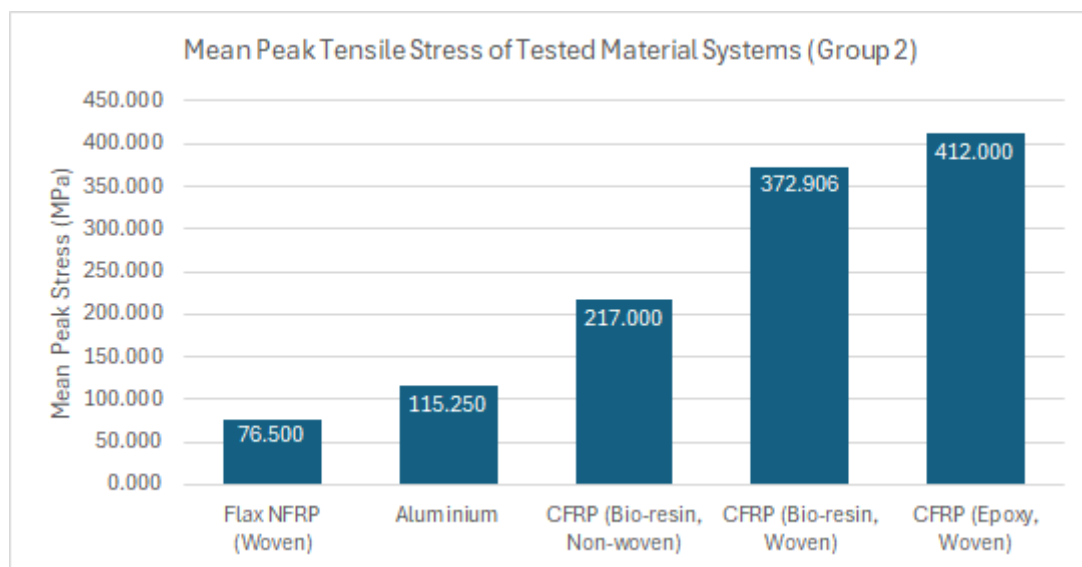


Figure 3: Mean peak tensile stress of tested material systems based on Group 2 tensile test data.

The stress–strain response in Figure 4 further highlights the different material behaviours. Woven CFRP reached high stress at low strain, indicating stiff behaviour and limited deformation before failure. In contrast, flax FRP produced a lower stress response with greater

deformation, reflecting its lower stiffness and more compliant fibre behaviour. Aluminium displayed the most distinct response, with yielding followed by extended plastic deformation. This shows the clear difference between ductile metallic behaviour and the more brittle tensile response of composite laminates (Callister Jr and Rethwisch 2020).

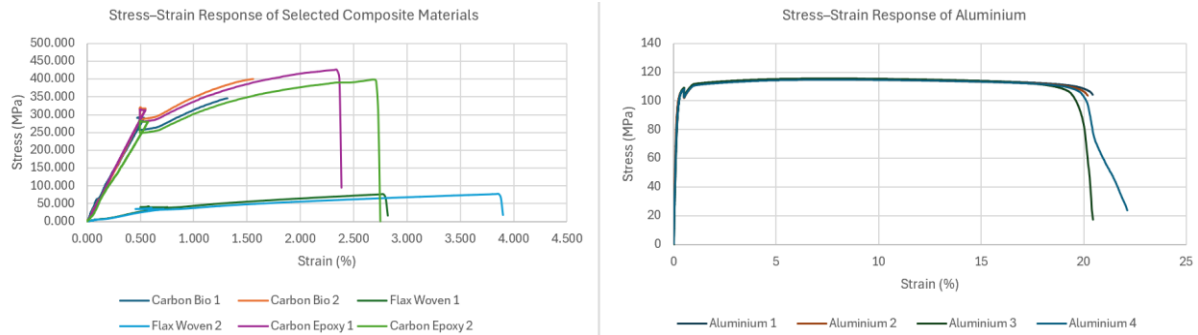


Figure 4: Stress-strain response of selected composite materials (left) and aluminium (right) from tensile testing.

Young's modulus was calculated from the initial linear region of each curve using extensometer strain data. As shown in Table 1, woven CFRP systems produced the highest stiffness values, with bio-resin CFRP remaining very close to epoxy CFRP. This supports the potential of matrix substitution where stiffness retention is required. Aluminium was also comparable, while non-woven CFRP and flax FRP were significantly lower. Supplier data supports this trend, with woven flax modulus values around 3.5–4 GPa, close to the experimental value of 4.95 GPa.

Table 1: Experimental Young's modulus values for tested material systems.

Material	Experimental Young's modulus (GPa)
Flax FRP (Woven)	4.95
CFRP (Bio-resin, non-woven)	18.14
Aluminium	54.67
CFRP (Bio-resin, Woven)	54.68
CFRP (Epoxy, Woven)	54.21

The mean failure strain results in Figure 5 further distinguish the different deformation behaviours. Aluminium exhibited the highest strain, reflecting significant plastic deformation before fracture. This is consistent with ductile metallic behaviour, where face-centred cubic (FCC) crystal structures provide multiple slip systems and enable greater plastic deformation before failure (Lim and Huh 2022). Conversely, the composite materials tested provide much lower strain values, with CFRP in bio-resin showing the lowest failure strain of 0.014. Woven

CFRP in epoxy and non-woven CFRP showed slightly higher values, while flax FRP had a higher value again, due to the more compliant fibre behaviour.

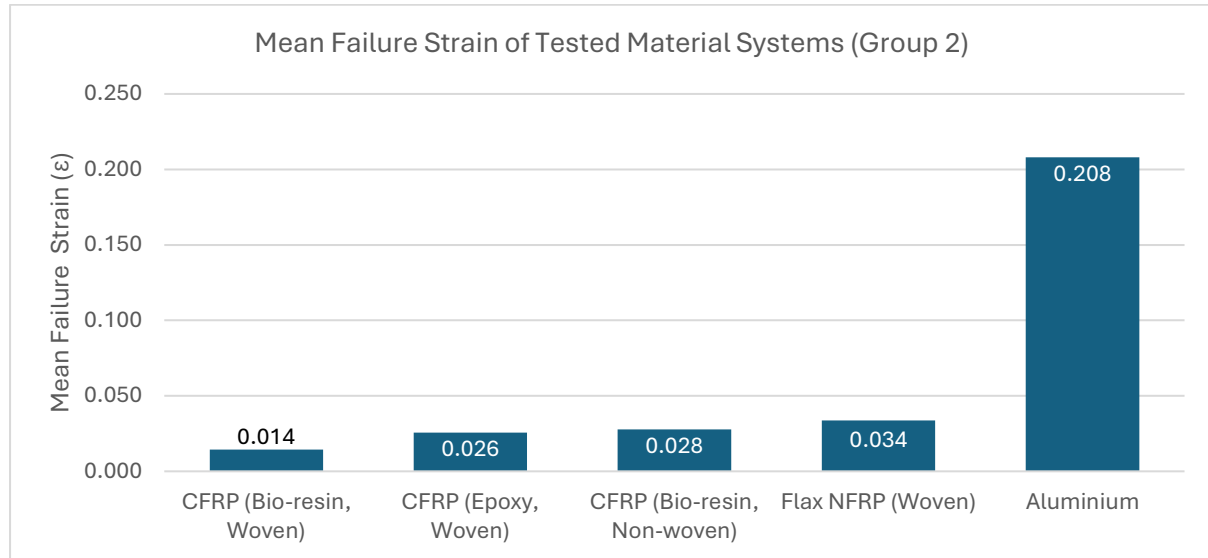


Figure 5: Mean failure strain of tested material systems based on Group 2 tensile testing.

The experimental results were also compared with theoretical upper and lower bounds calculated using the law of mixtures, as shown in Table 2. For the CFRP samples, a 50:50 fibre-to-matrix volume fraction was assumed according to the testing plan, while flax values were taken from supplier datasheets. Woven CFRP modulus values fell within the theoretical range, supporting the validity of the experimental results. The measured peak stresses were closer to the lower theoretical bounds, suggesting that fibre orientation, woven architecture and manufacturing quality limited full fibre utilisation. The similarity between epoxy and bio-resin CFRP stiffness values further suggests that matrix substitution had limited effect on elastic response in this test context.

Table 2: Law of mixtures comparison between theoretical bounds and experimental tensile results.

	Elastic (GPa)	Tensile (MPa)	Experimental Young's	Experimental Peak Stress
Flax FRP (Woven) Upper	4.04	65.964	4.95	76.500
Flax FRP (Woven) Lower	3.59	65.731		
CFRP (Bio-resin, Non-woven) Upper	16.52	49.2	18.14	217.000
CFRP (Bio-resin, Non-woven) Lower	5.52	41.71		
CFRP (Bio-resin, Woven) Upper	118.52	2094.2	54.68	372.906
CFRP (Bio-resin, Woven) Lower	6.00	134.6		
CFRP (Epoxy, Woven) Upper	118.65	2097.5	54.21	412.000
CFRP (Epoxy, Woven) Lower	6.51	147.32		

5 Sustainability Analysis

Composite sustainability must be evaluated across the full product lifecycle, including raw material extraction, manufacturing, service performance and end-of-life management. This is particularly important in automotive, motorsport and motorcycle applications, where low mass can improve efficiency, but material choices must also respond to environmental pressure, recyclability limitations and future legislation.

5.1 Material Extraction and Resource Impact

Carbon fibre production remains energy-intensive, with fibres commonly produced from polyacrylonitrile (PAN) precursors through high-temperature stabilisation and carbonisation. This gives CFRP excellent mechanical potential but also creates a high embodied environmental burden at the raw-material stage. In contrast, flax fibres are renewable agricultural materials with lower processing demands and potential carbon sequestration during growth, giving natural fibre composites a clear advantage in resource sourcing (Yan et al. 2014; Eleutério et al. 2025).

However, this advantage depends on functional performance. If a lower-impact material requires greater volume, reinforcement or shorter service life, some raw-material benefit may be reduced. Flax-based composites are therefore most convincing where their lower environmental impact can be used without forcing unrealistic structural substitution.

5.2 Manufacturing and Processing

Manufacturing is another major contributor to composite environmental impact. Conventional CFRP production can involve energy-intensive fibre manufacture, resin curing and, in higher-performance applications, autoclave processing. These stages increase carbon footprint, particularly where high temperature, pressure or long curing cycles are required. Bio-resin systems can reduce reliance on petrochemical matrices by incorporating renewable feedstocks. In this study, the comparison between woven CFRP in epoxy and bio-resin suggests matrix substitution can improve sustainability without a major stiffness penalty, retaining the mechanical advantages of carbon fibre reinforcement.

Processing control remains especially important for natural-fibre composites. Chen et al. (2020) reported unidirectional flax FRP tensile strength varying from 69.69 to 123.02 MPa, partly due to resin volume fraction differences during wet lay-up, while natural fabric moisture ratios ranged from 5–12%. This shows that fibre drying, resin impregnation and fibre–matrix

adhesion must be carefully controlled if natural-fibre composites are to deliver consistent performance. Moisture sensitivity is also a wider limitation, as water absorption can degrade fibre–matrix bonding and reduce long-term mechanical reliability (Alajmi et al. 2022).

5.3 Performance and Structural efficiency

A sustainability assessment must also consider how efficiently a material provides useful mechanical performance. Lower-impact materials are only beneficial if they can meet the functional requirements of the component without requiring excessive material, reinforcement or replacement (Le Duigou and Baley 2014).

The experimental results show that the tested woven CFRP systems provided significantly higher tensile strength and stiffness than the flax NFRP, making them more efficient for highly loaded structural applications. This agrees with published data: Chen et al. (2020) reported CFRP laminate tensile strength of 2874.25 MPa compared with 69.69–123.02 MPa for flax FRP. Similarly, Zouhar et al. (2022) reported tensile strengths of 760 MPa for carbon twill, 463 MPa for carbon–flax hybrid and 115 MPa for flax twill. These values demonstrate the clear tensile-performance penalty associated with flax-only systems, while also showing that hybridisation can recover part of the performance gap.

This supports a selective rather than absolute approach to sustainable substitution. CFRP remains the strongest option where maximum tensile performance and stiffness are required. However, Zouhar et al. (2022) also reported a 50% lower frequency response function for a carbon–flax hybrid component compared with a carbon-only part, suggesting that flax-based or hybrid systems may provide value in secondary structures where damping, reduced mass and lower environmental impact are beneficial.

5.4 End-of-Life Management

End-of-life management plays a significant role in the overall sustainability of engineering materials. Aluminium has a clear advantage because it has established recycling infrastructure, high recovery potential and comparatively low reprocessing energy. In contrast, CFRP is more difficult to recycle because the fibres are embedded within a polymer matrix, making fibre separation and recovery technically challenging.

Recycling routes such as pyrolysis, solvolysis and mechanical recovery are under development. Witik et al. (2013) show that CFRP recycling can reduce environmental burden compared with landfill or energy recovery, although the benefit depends strongly on the

selected recovery route. Meng et al. (2018) similarly show that life-cycle energy and global warming potential are strongly affected by recovered fibre quality and process energy demand. However, recovered fibres often suffer property reduction, and large-scale closed-loop recycling remains limited, reducing the current sustainability advantage of CFRP recycling (Witik et al. 2013; Meng et al. 2018; Tapper et al. 2020).

Natural-fibre composites offer improved end-of-life potential, particularly where renewable fibres and bio-based matrices are used. Bensadoun et al. (2016) and Beigbeder et al. (2019) show that flax-based and bio-based composites can reduce environmental burden under suitable disposal scenarios. However, complete biodegradability is often limited by the polymer matrix, meaning NFRP systems should be treated as an improvement over conventional composites rather than a fully circular solution.

5.5 Overall Sustainability Assessment

Overall, no single material provides the best outcome across all sustainability and performance criteria. CFRP offers superior structural efficiency but carries high embodied impact and difficult end-of-life recovery. Flax-based NFRP has clear advantages in renewable sourcing and potential end-of-life impact, but its lower tensile strength and stiffness restrict its use in highly loaded applications.

The most realistic route is selective substitution rather than complete replacement. Bio-resin CFRP offers a practical near-term improvement by reducing matrix-related impact while retaining carbon reinforcement stiffness. Flax-based NFRP and carbon–flax hybrids are better suited to secondary or non-critical structures, where reduced impact and improved damping can be used without compromising primary structural performance (Le Duigou and Baley 2014; Zouhar et al. 2022).

6 Recommendations

Based on the experimental results and later sustainability analysis, complete replacement of CFRP with a flax FRP alternative is not a viable option for high loaded vehicle components. CFRP should remain the preferred option where high stiffness, strength and low mass are essential, as its performance advantages are well established in automotive composite applications (Othman et al. 2018; Chen et al. 2020). However, its high embodied impact and current challenging EoL recovery mean it should be used selectively rather than as a default material.

Where carbon reinforcement is still required, bio-resin CFRP should be investigated further. The experimental results suggest that carbon in bio-resin can retain useful stiffness while reducing reliance on conventional petrochemical resins. This makes matrix substitution a practical near-term improvement, particularly where full natural-fibre replacement would compromise performance.

For secondary structures, semi-structural panels and less critical components, carbon–flax hybrids provide the strongest sustainability opportunity. Hybridisation can reduce the total carbon content while retaining more useful mechanical performance than a full flax replacement, and previous studies show that natural-fibre systems can reduce the environmental impact when applied in suitable structural contexts (Duflou et al. 2014; Le Duigou and Baley 2014; Zouhar et al. 2022). Flax-only FRP is therefore reserved for minimally loaded or non-structural components unless improved fibre alignment, laminate quality or hybrid reinforcement is introduced.

Further sustainability research should also investigate alternative natural fibres rather than treating flax as the only viable NFRP route. Fibres such as hemp, jute, kenaf or basalt may offer different balances between mechanical properties, moisture sensitivity, availability and environmental impact, and could be assessed against flax using the same tensile, durability and lifecycle criteria (Yan et al. 2014; Eleutério et al. 2025).

Further investigation should cover fatigue, impact, moisture ageing and larger-scale component testing, as tensile testing alone does not represent the breadth of conditions across automotive, motorsport, and motorcycle industries. This is particularly important for NFRP, where moisture sensitivity and fibre–matrix bonding can affect long-term reliability (Alajmi et al. 2022). EoL planning should also be considered during design, since CFRP recycling remains limited by recovered fibre quality, process energy and industrial scalability (Witik et al. 2013; Meng et al. 2018; Tapper et al. 2020).

7 Conclusion

This report has shown that sustainable composite selection in automotive, motorsport and motorcycle applications cannot be judged by environmental credentials alone. The tensile results confirmed that reinforcement architecture and fibre type had a major influence on performance, with woven CFRP providing the highest strength and stiffness, while flax FRP remained mechanically limited despite its lower-impact origin. The similarity between the epoxy and bio-resin CFRP stiffness results also showed that some sustainability improvements may be possible without complete fibre replacement.

The main finding was that sustainability depends on matching the material to the duty of the component. CFRP remains difficult to displace in the most critical applications because its structural efficiency reduces the amount of material needed to achieve the required performance. However, its production impacts and EoL limitations reduce its environmental credibility when it is used unnecessarily. NFRP offers a useful alternative, but only where lower strength, moisture sensitivity and durability limitations do not create greater lifecycle penalties through over-design or reduced service life.

Overall, the most credible sustainability pathway for critical structures is not total replacement, but selective substitution. Future development should focus on reducing carbon content where possible, improving matrix sustainability, designing components with EoL recovery in mind and validating promising materials under service-relevant conditions beyond tensile loading. This approach offers a more realistic route to lowering environmental impact while maintaining the performance standards expected in high-performance vehicle engineering.

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