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Materials Testing and Sustainability of Composites
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1 Introduction

Material selection is a crucial part of motorsport and automotive engineering, where components must balance high mechanical performance with low mass, reliability and manufacturability. Traditionally, synthetic composites such as carbon fibre and Kevlar have dominated high-performance applications due to their exceptional stiffness-to-weight ratios and ability to be tailored to specific loading conditions. However, increasing environmental pressures and tightening legislations are reshaping how materials are evaluated within the sector. Motorsport UK, the FIA and UK Government with Net Zero policies are now emphasising reduced carbon emissions, improved recyclability and circular-economy integration, requiring engineers to consider sustainability alongside performance.

These pressures are particularly relevant to composites, which offer significant use-phase benefits through weight reduction but often have high manufacturing energy demands and limited end-of-life recovery. Natural fibres such as flax present a lower-impact alternative, though with reduced stiffness and greater variability. Metals such as aluminium remain widely used due to their recyclability and established manufacturing routes, yet their primary production is energy-intensive. Understanding these trade-offs is essential for selecting materials that meet both performance requirements and emerging sustainability expectations.

This report investigates the mechanical performance and sustainability of aluminium, carbon fibre, flax and Kevlar through experimental tensile testing and lifecycle analysis. Experimental results are validated against manufacturer data and theoretical predictions using the law of mixtures. The findings are then evaluated in the context of current and future sustainability legislations, leading to recommendations on the suitability of each material for structural and non-structural applications within motorsport and automotive engineering.

2 Literature Review (800-1000)

Composite materials are widely used in automotive and motorsport applications due to their high strength, stiffness and ability to be tailored to specific loading conditions. Carbon fibre dominates structural and aerodynamic components such as bodywork, while natural fibres such as flax are used for non-structural applications due to their low environmental footprint. Kevlar is popular for impact resistance structures, and aluminium continues to dominate the metals due to its lightweight structure that is highly manufacturable and recyclable.

2.1 Materials tested

2.1.1 Aluminium

Aluminium is a commonly used material in motorsport and automotive applications due to its high strength-to-weight ratio and excellent manufacturability. It typically exhibits a Young's Modulus typically is around 70GPa (Granta, 2024), making it suitable for lightweight structural components. Its high formability allows rapid production of complex geometries, contributing to its use in chassis, brackets and housings. Although primary production is energy intensive, aluminium is highly recyclable with minimal loss of properties, giving it a strong circular economy potential.

2.1.2 Carbon non-woven, woven bio and epoxy

Carbon non-woven bio composites consist of randomly oriented fibres embedded within a bio-based epoxy matrix, producing a laminate with moderate stiffness and relatively high tensile performance due to the absence of fibre crimp (Ramachandran et al., 2023). In contrast, woven composites use fibres arranged in defined orientations, improving formability and impact resistance for applications such as bodywork and crash structures. However, the interlaced architecture introduces crimp at the weft-warp intersections, reducing tensile efficiency compared with non-woven systems.

With increasing sustainability pressures in motorsport, bio-based resins are being adopted as an alternative to petroleum-derived epoxies. Literature indicates that modern bio-epoxies can achieve comparable performance to conventional epoxies (Ramachandran et al., 2023), offering an improved environmental profile without compromising structural integrity. This makes them suitable for applications where sustainability influences material selection, even though the carbon fibres themselves remain difficult to recycle.

Carbon composites exhibit significantly higher tensile strength and stiffness-to-weight ratios than aluminium. Their lower density enables superior properties, meaning that for equal mass, carbon-based composites carry substantially higher loads. This advantage explains their continued dominance in high-performance structural applications.

2.1.3 Flax woven vs non woven bio

Flax fibres are plant-based reinforcements valued for their low embodied energy and reduced environmental impact compared with synthetic fibres (Faruk et al., 2012). Their mechanical performance depends strongly on fibre architecture, with woven flax typically achieving higher stiffness and strength, while non-woven mats show reduced tensile properties due to poor fibre alignment and limited resin infiltration (Phongam et al., 2015). Flax is therefore commonly used in interior or semi-structural automotive components where weight reduction and sustainability are prioritised over peak mechanical performance. Hybrid flax-carbon laminates have also been explored to improve sustainability while retaining acceptable structural capability (Bachmann, Wiedemann and Wierach, 2018).

2.1.4 Kevlar woven bio

Kevlar is a high-performance synthetic aramid fibre known for its high tensile strength, toughness and low density (Hatton, 2019), making it suitable for impact-resistant components in motorsport applications. Its woven architecture enhances energy absorption but offers lower compressive strength than carbon fibre, limiting its use in load-dominated structural conditions. As a petroleum-derived fibre, Kevlar carries a higher environmental burden than natural alternatives, and its recyclability remains limited. Despite this, Kevlar remains widely used where damage tolerance and penetration resistance are prioritised over stiffness (Zhou et al., 2022).

2.2 Comparative

Literature consistently identifies carbon fibre as the highest-performing material in terms of strength-to-weight ratio and stiffness, although it offers limited recyclability compared to aluminium. Aluminium provides lower tensile strength but far greater ductility and manufacturability, making it a reliable baseline material. Fibre architecture strongly influences composite behaviour, with woven architecture achieving higher directional stiffness, while non-woven systems show reduced tensile efficiency due to fibre misalignment. Natural fibres such as flax offer lower mechanical performance but improved environmental impact through reduced density and embodied energy. These contrasts establish the expected performance used to benchmark the experimental results.

3 Sustainability Analysis

Sustainability is a significant factor in engineering design, especially recently with increasing legislative pressure to reduce emissions and transition towards Net Zero. In motorsport and automotive sectors, material choices are now influenced not only by performance but also by embodied energy, recyclability and end-of-life impacts. Regulations from motorsport leaders and the UK government are pushing manufacturers to adopt lower-carbon materials and improve circular-economy practices. As a result, engineers must evaluate the full lifecycle of materials and balance high mechanical performance with environmental responsibility.

3.1 Lifecycle Analysis

3.1.1 Resource Extraction

Aluminium extraction relies on bauxite mining which requires large land areas for ore processing and contributes to a large amount of greenhouse gases (Nunez and Jones, 2015). Carbon fibre production begins with oxidation and carbonisation of polyacrylonitrile (PAN) fibres, a process that is energy-intensive. In contrast, flax fibres originate from agricultural sources and therefore have a significantly lower embodied energy. However, flax fibre quality is highly sensitive to environmental conditions, including fertiliser levels, soil type, climate and harvest timing, all of which introduce variability in mechanical performance (Ramachandran et al., 2023). Although bio-composites offer clear environmental advantages, these inconsistencies and their sensitivity to moisture limits their suitability for important structural components such as bodywork or crash structures. Kevlar is a petroleum derived aramid fibre which largely depends on non-renewable feedstocks and chemical synthesis, giving it a large embodied energy in comparison to natural fibres.

3.1.2 Manufacturing Energy & Emissions

Carbon fibre manufacturing is characterised by extremely high energy consumption, with global warming potential of approximately 54 kg CO₂e – around 4-5 times higher than flax-based bio-composites (Ramachandran et al., 2023). The stabilisation and carbonisation stages alone make carbon fibre several times more energy-intensive than natural-fibre alternatives. Flax, by contrast, has substantially lower manufacturing energy (Ramachandran et al., 2023). Aluminium production is also highly-energy demanding, with significant CO₂ emissions associated with bauxite extraction and electrolytic smelting (Alamdari, 2017). Kevlar exhibits similarly high embodied energy, with polymerisation and fibre spinning processes giving it a manufacturing footprint comparable to other synthetic fibres (Han et al., 2025).

3.1.3 Use-Phase Benefits

Although carbon fibre carries a high manufacturing burden, its lightweight properties deliver substantial use-phase benefits. In motorsport (Cecchel, 2020) and general mechanical, specifically aviation (Timmis et al., 2014), carbon fibre components used in replacement of aluminium reduce CO₂ and NO_x emissions by ~20% due to improved aerodynamic and reduced mass, as well as reducing overall fuel consumption. As a result, the environmental “debt” associated with carbon fibre production is typically repaid early in the component’s service life. This performance advantage explains its continued dominance in high-performance applications. Aluminium also provides meaningful use-phase benefits through weight reduction compared with steel, contributing to lower fuel consumption and higher performance in automotive and motorsport applications respectively. Natural fibres such as flax offer limited use-phase advantages due to their restricted structural capability. Kevlar provides minimum weight-saving benefit compared with carbon fibre, but its toughness improves durability and safety in impact-critical components.

3.1.4 End-of-Life & Recyclability

Carbon fibre technologies have advanced significantly, with pyrolysis (typically above 500°C (Liu et al., 2019)) enabling the recovery of high-quality fibres. However, resin systems are generally lost during this process and recycling rates remain low compared to metals.

Aluminium is one of the most recyclable engineering materials, with well established remelting routes and the potential for very low end-of-life impact (Soo et al., 2018).

Flax fibres are biodegradable, but recyclability of flax-based components depends heavily on the resin system, with thermoset resins limiting recovery (Ramachandran et al., 2023). Kevlar remains difficult to recycle due to its chemical stability, and although pyrolysis can recover fibres (Liu et al., 2019), the resulting material typically exhibits reduced mechanical performance.

3.2 Comparison and discussion

Across the full life cycle, the materials tested present distinct sustainability trade-offs. Flax-based composites offer the lowest embodied energy and minimal environmental burden during production, but their limited structural capability restricts the scale of use-phase emissions savings. Carbon fibre sits at the opposite extreme. Its manufacturing footprint is the highest, yet its exceptional stiffness-to-weight ratio enables substantial operational reductions in fuel consumption and emissions, often repaying its initial environmental “debt” early in service. Aluminium occupies a middle ground, with high production energy but excellent recyclability that supports circular-economy targets. Kevlar provides valuable impact resistance but offers few sustainability advantages due to its petroleum origin and poor end-of-life recovery.

These trade-offs must be interpreted in the context of tightening sustainability legislation. Motorsport UK and the FIA have introduced environmental frameworks such as the FIA Environmental Accreditation Programme and Motorsport UK’s Sustainability Strategy, both of which encourage reduced embodied carbon and improved material recovery. At a national level, the UK’s Net Zero Strategy and the Environmental Act 2021 place increasing pressure on manufacturers to adopt lower-carbon materials and support circular economy practices. These policies collectively drive a shift toward materials with lower lifecycle impacts, greater recyclability and reduced reliance on fossil fuels. As a result, material selection in motorsport and automotive engineering increasingly requires balancing high performance with compliance to emerging environmental standards.

4 Experimental testing

4.1 Methodology

Material testing was carried out on a variety of specimens to compare the mechanical performance and to generate experimental values for validation. Aluminium, Carbon (woven bio-WB, non-woven bio-NWB and woven epoxy-WE), Flax (non-woven-NWB and woven bio-WB), and Kevlar samples were tested. All force, extension, stress and strain data was recorded by the machine's integrated software. Each sample was measured for width and thickness before being clamped in the tensile testing machine. Strain was measured using an extensometer (Figure 1), which was removed before material failure, and stress was calculated by the applied load and the input cross-sectional area. The samples were visually inspected for any defects or likely failure points prior to testing.

A consistent test procedure was followed for all materials. Each clamped under the same configuration, and the machine applied a constant displacement rate throughout the test. The same gauge length was used for all extensometer measurements, and all tests were conducted under ambient conditions. The test was run until complete failure of each specimen.

Potential error sources include small variations in thickness, natural fibre variability in flax samples, and the possibility of stress concentration near the grips. Removing the extensometer before failure may have also reduced the accuracy of the final strain measurements.

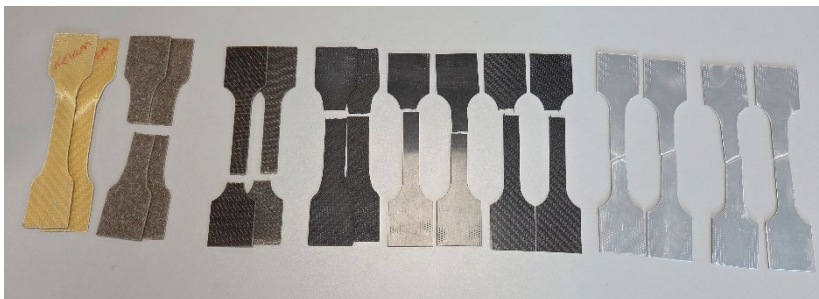


Figure 2 Samples used for testing



Figure 1. Extensometer on specimen

Table 1. Cross-sectional area of selected samples

	Cross-sectional area (mm ₂)						
	Aluminium	Carbon NWB	Carbon WB	Carbon WE	Flax NWB	Flax WB	Kevlar
1	22.5	20.44	15.95	13.65	23.76	32.52	9.7
2	22.5	29.96	22.5	13.65	23.76	33.95	9.6
3	22.5	19.84	30	10.22	23.98	34.56	30
4	22.5	7.36	13.58	11.68	19	25.5	19.33
5	22.5	5.64	15.68	10.88	26.73	28.02	17.96

4.2 Results and Analysis

The raw data was exported from the testing machine and processed in MATLAB to plot stress-strain curves and calculate mechanical properties. Five samples from each material were selected based on how they fitted against each other on the plots, while several others were excluded due to incomplete strain capture or irregular failure behaviour. Limiting the dataset ensured consistent comparison between materials and produced clear, interpretable graphs for subsequent analysis.

4.2.1 Aluminium

The Aluminium samples exhibit consistent tensile response across all tests. The graph shows an initial elastic region followed by a yield point at ~110MPa stress. Beyond this, the material shows a relatively stable plateau indicating plastic deformation. As strain increases, a gradual reduction in stress occurs, corresponding to necking prior to fracture. Failure occurs over a broad range of 12-16%, demonstrating significant ductility. While peak stress values are similar across samples, variation in failure strain suggests inconsistencies in geometry or localised defects influencing the early necking. Overall the repeatability of the curves indicates reliable test conditions, with aluminium displaying stable plastic behaviour and predictable failure characteristics.

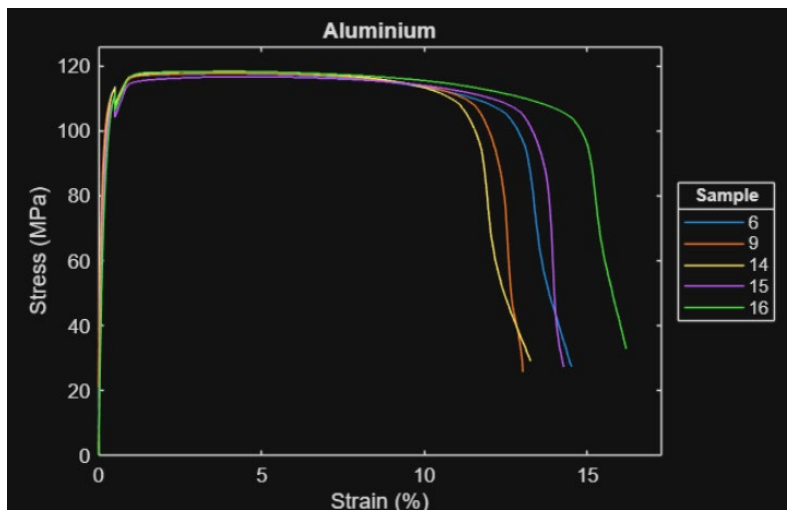


Figure 3. Aluminium stress-strain graph

Table 2. Modulus variance for aluminium samples

Sample	Modulus (GPa)
6	55.58
9	56.02
14	49.73
15	49.64
16	40.2

4.2.2 Carbon Fibre

Table 3. Carbon fibre Youngs Modulus comparisons

Non-Woven Bio		Woven Bio		Woven Epoxy	
Sample	Modulus (GPa)	Sample	Modulus (GPa)	Sample	Modulus (GPa)
1	16.51	3	50.78	8	70
2	12.9	5	33.82	9	56.3
8	1.44	6	26.4	13	63.11
18	22.08	7	61.75	14	58.13
19	12.77	13	56.63	17	48.94

Figure 4 shows that Carbon fibre samples exhibit significantly higher tensile stress than aluminium, but fail at much lower strain, reflecting their brittle behaviour. The non-woven bio reaches the highest stiffness and peak stress, ~550MPa, followed by the woven epoxy and then the woven bio. The woven epoxy shows the steepest initial slope, indicating the highest stiffness, but fails earlier than the non-woven system. The woven bio demonstrates the lowest stiffness and peak stress of the three. All carbon systems fail abruptly with no

evidence of plastic deformation. A small loop is visible at approximately 0.5% strain on all samples, indicating the point at which the machine fully tensions the fibres and the extensometer stabilises before entering the true linear elastic region.

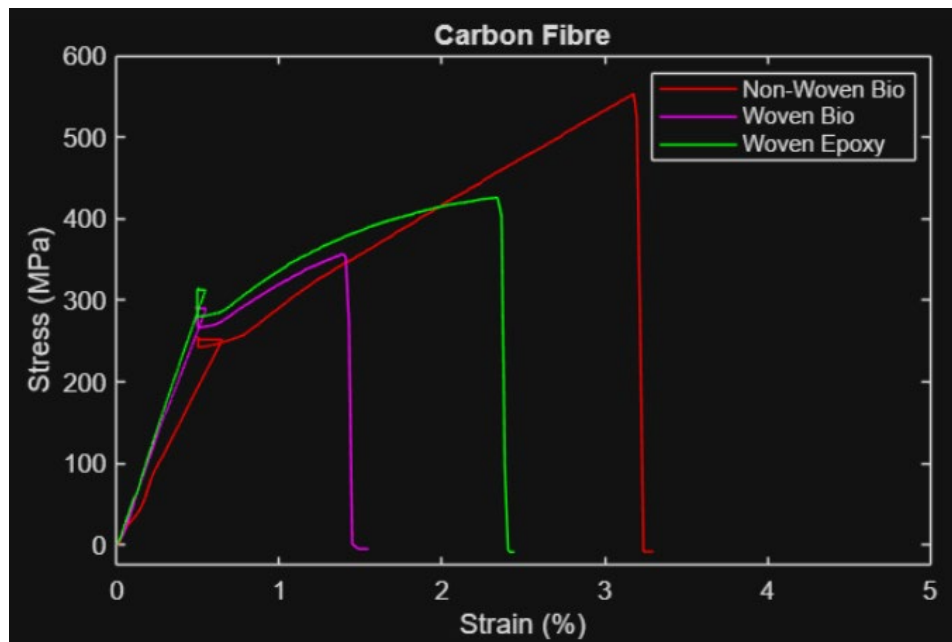


Figure 4. Carbon Fibre architecture and resin comparison

4.2.3 Flax

The woven flax reaches higher stress values than the non-woven sample across the entire strain range. It shows a steeper initial slope, indicating higher stiffness, while the non-woven sample exhibits a more gradual stress-strain response with lower peak stress. Woven sustains a greater strain before failure, almost twice as much, whereas the non-woven sample fails earlier and at a much lower stress. Both architectures show abrupt failure with no evidence of plastic deformation, and the tension loop is visible on all samples. In

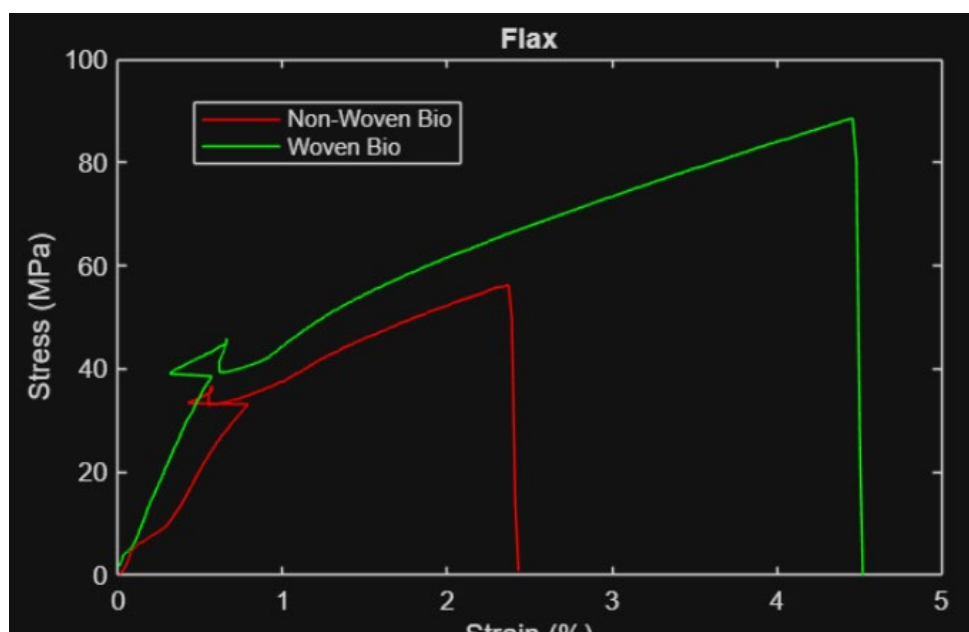


Figure 5. Flax woven vs non-woven

comparison to carbon fibre, both variations of flax experience less than non-woven carbon, proving that it is suitable for non-structural components.

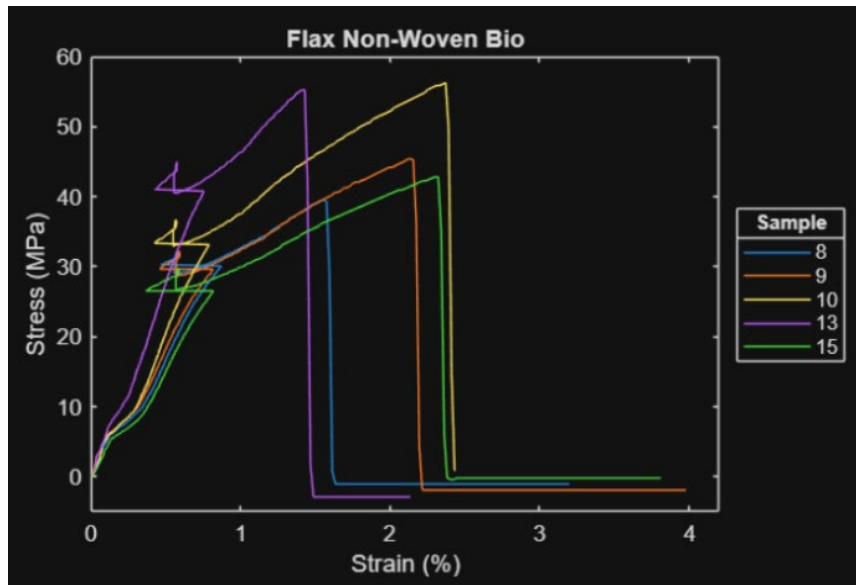


Figure 6. Flax non-woven bio samples variation

The non-woven bio samples show large variation in results, suggesting that the material is inherently inconsistent under tensile loading, with noticeable scatter in stiffness, peak stress and failure strain. This variability is evident in the carbon composites, indicating that neither composite system demonstrates fully repeatable behaviour under the test conditions.

4.2.4 Kevlar

The Kevlar samples show substantial variability in tensile performance, with peak stress ranging from ~150MPa to nearly 600MPa. The initial elastic slopes also differ noticeably between specimen, samples 2 and 3 display steep initial gradients, while sample 7 shows a more gradual rise, reflecting significant variation in stiffness. This behaviour aligns with the large differences in cross-sectional area recorded across the samples (Table 1), which ranged from 9.6 to 30, directly influencing the calculated stress values. Failure strain is similarly inconsistent, with some samples failing at relatively low strain and others sustaining deformation beyond 5% before fracture. All composite samples show abrupt failure and have no display of plastic deformation. The highest-performing Kevlar samples reach peak

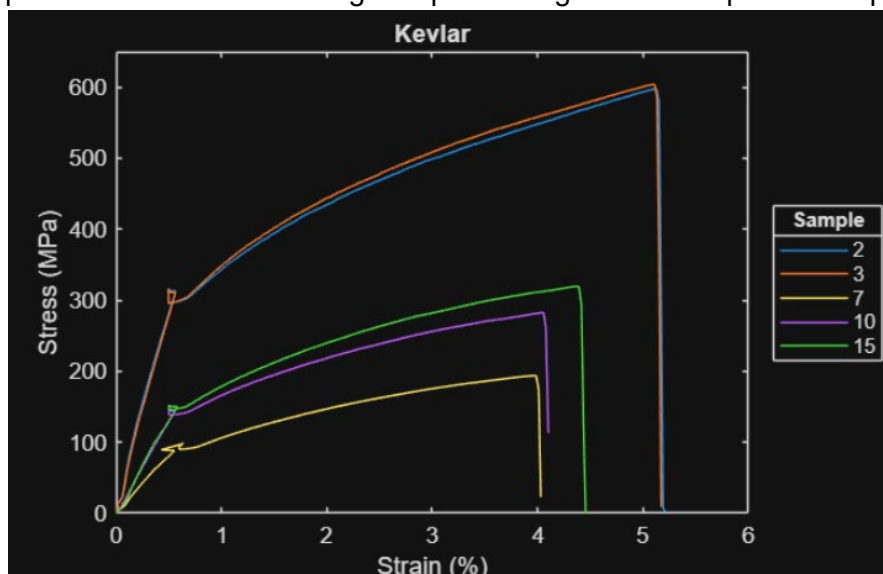


Figure 7. Kevlar samples stress-strain graph

stresses comparable to the carbon non-woven bio sample, while the lower-performing specimens fall closer to the flax woven range, reinforcing that composite properties depend strongly on lay-up and geometric uniformity.

4.2.5 Comparisons

Table 4. Comparison of all materials

	UTS (MPa)	Youngs Modulus (Avg GPa)	% Variance	Failure Strain %
Aluminium	117.85	48.90	12.72	16.2
Carbon Non-Woven Bio	273.69	12.30	57.50	3.3
Carbon Woven Bio	338.76	44.65	32.99	2.41
Carbon Woven Epoxy	420.93	56.62	13.24	2.75
Flax Non-Woven Bio	47.88	6.27	61.46	4.22
Flax Woven Bio	85.73	1.71	16.48	4.62
Kevlar	392.45	16.43	60.30	5.21

Across all materials, aluminium is the only sample to show ductile behaviour, while every composite exhibits sudden brittle failure. Aluminium also demonstrates the highest consistency between tests attributed to the consistent cross sectional area of the samples, with carbon woven epoxy showing similarly low variation which also has a mostly consistent cross-sectional area. In contrast, the carbon systems achieve the highest UTS values overall, with Kevlar approaching performance of the woven epoxy samples. The low failure strain of all carbon samples reinforces their ability to withstand high stresses but minimal deformation. Variability is most pronounced in flax non-woven and Kevlar, reflecting the influence of natural fibre inconsistency and lay-up sensitivity. Some of this scatter is likely linked to differences in cross-sectional area, particularly in Kevlar and non-woven systems, which further reduces the reliability of their measured stiffness and strength.

When linked to sustainability, these mechanical trends show that materials capable of maintaining high stiffness and strength for longer (such as carbon fibre and aluminium) offer greater durability and therefore reduced replacement frequency and end-of-life impact. Conversely, materials with high variability or lower structural capability, such as flax and Kevlar, may require more conservative design margins or more frequent replacement, influencing their overall sustainability performance.

4.3 Validation

Table 5. Youngs Modulus values compared with research and Law of Mixtures

	Youngs Modulus (GPa)			
	Experimental	Granta	Law Of Mixtures Upper	Lower
Aluminium	48.90	69-72	-	-
Carbon Non-Woven Bio	12.30	-	14.02	5.42
Carbon Woven Bio	44.65	58-64	118.52	6.00
Carbon Woven Epoxy	56.62	-	118.65	6.51
Flax Non-Woven Bio	6.27	8-12	5.88	3.43
Flax Woven Bio	1.71	-	3.61	3.36
Kevlar	16.43	5.5-8	-	-

The experimental Young's Modulus values were compared against manufacturer data (Granta, 2024) and where applicable, theoretical predictions using the law of mixtures (method in Appendix). The results are summarised in Table 5, with Carbon Woven-bio and Aluminium showing the closest agreement to Granta, suggesting that although the stiffnesses varied widely, the majority of samples were in the correct region, with a small

number of anomalies reducing the average. All composites recorded lower stiffness than expected, which is consistent with low fibre volume fractions, imperfect fibre alignment and the presence of voids in hand-layup laminates. In several cases, the experimental modulus remains within the law-of-mixtures bounds, reflecting the sensitivity of the model to assumed high quality fibre alignment. Overall repeatability was acceptable, with consistent trends across specimens, but natural-fibre variability and laminate non-uniformity reduced reliability compared with synthetic composites.

5 Recommendations

Based on the experimental results and sustainability analysis, several recommendations can be made regarding the use of composite materials in automotive and motorsport applications. Carbon-based composites demonstrated the highest stiffness of all materials tested, with woven epoxy showing the strongest performance, making it the most suitable option for structural components where weight reduction and mechanical efficiency are critical. However, their high embodied energy and limited recyclability means they should be prioritised only where performance benefits clearly outweigh environmental impact. Aluminium, despite testing below its expected modulus, remains a reliable, fully recyclable option and aligns well with current legislation emphasising circular-economy practices. Flax composites showed the lowest stiffness and highest variability, restricting their use to non-structural panels or secondary components where sustainability is prioritised over performance. Kevlar offered moderate stiffness but limited end-of-life recovery, suggesting its use should be reserved for impact-critical applications only. Future work should focus on improving fibre volume fraction, reducing void content and exploring bio-resins and hybrid laminates to enhance the sustainability of composite structures.

6 Conclusion

The findings of this study highlight the tension between mechanical performance, manufacturing quality and sustainability in composite material selection. The experimental results showed clear performance ranking, but the high variability in several composites (particularly flax and Kevlar) demonstrates that material capacity is strongly dependent on fibre architecture, lay-up consistency, fibre volume fraction and cross-sectional area. This variability reduces confidence in their use of structurally demanding applications, regardless of their sustainability advantages. In contrast, carbon fibre consistently delivered the highest stiffness, yet its environmental footprint and limited recyclability restrict its suitability to applications where performance gains justify the impact. Aluminium, while mechanically inferior to carbon, demonstrated excellent repeatability and strong alignment with circular-economy objectives, reinforcing its continued relevance in lightweight structures.

When interpreted alongside lifecycle and legislative pressures, the results indicate that no single material satisfies both performance and sustainability criteria. Instead, the data suggests a need for hybrid approaches, improving manufacturing control and greater emphasis on end-of-life strategies. The study also highlights the importance of accurate material data and realistic theoretical models, as discrepancies between experimental and predicted values significantly influence engineering decisions. Overall, sustainable material selection will depend on balancing performance requirements with environmental constraints, supported by improved processing methods and more robust composite design.

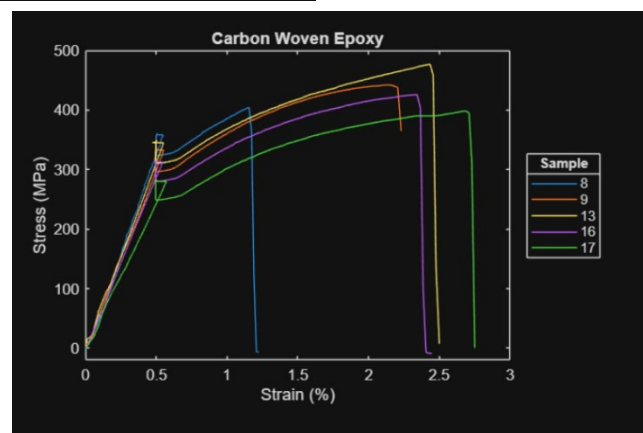
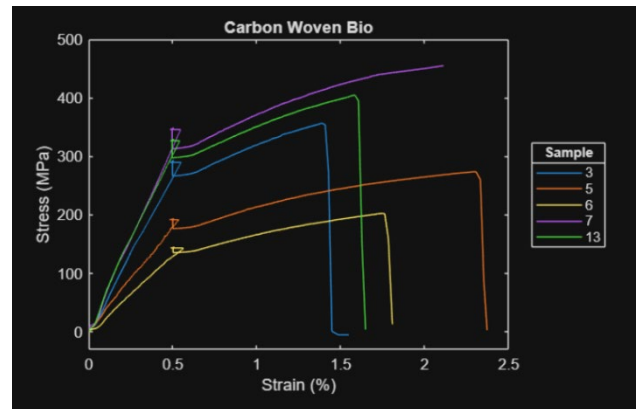
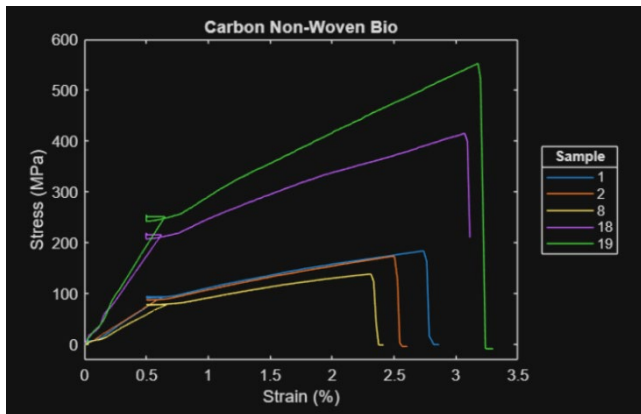
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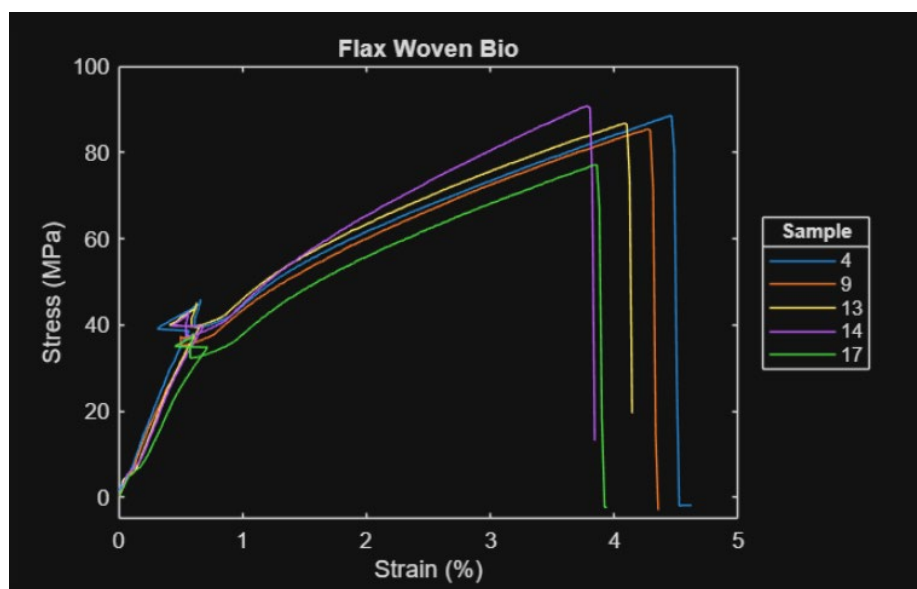
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Appendix

Carbon fibre sample graphs separately:



Flax woven bio:



Law of mixtures

Variable	Matrix modulus (E_m) in GPa	Resin volume fraction (V_m)
Epoxy resin	3.3	$1-V_p$
Bio-resin	3.04	$1-V_p$
	Particle (Fibre) modulus (E_p)	Fibre volume fraction (V_p)
Carbon woven	234	0.5
Carbon non-woven	25	0.5
Flax woven	6.5	0.29
Flax non-woven	5	0.18

*all data in above table taken from supplied datasheets

Upper limit:

$$E_c = (E_m \times V_m) + (E_p \times V_p)$$

Lower limit:

$$E_c = \frac{E_m \times E_p}{(V_m \times E_p) + (V_p \times E_m)}$$

These equations were used to calculate the upper and lower Youngs Modulus limit of the best performing laminate and to compare with experimental results in Table 5.