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**Materials testing and Sustainability of Composites for
Motorsport and Automotive Industries**

Automotive Materials and Sustainability
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Abstract

The automotive and motorsport industries are increasingly driven by the need to balance high performance material selection whilst undergoing the pressures of ever tightening sustainability regulations. This study investigates the mechanical performance and lifecycle impact of various types of materials.

- Carbon reinforced polymers
- Recycled carbon fibre
- Flax fibres
- Kevlar
- Aluminium (Benchmark)

This report goes through literature and lifecycle assessments as well as going through data gathered through a tensile test that had been conducted within groups.

The results demonstrate how CFRPs provide for the highest performance, whilst recycled carbon provides for a good low impact alternative seeing as it features moderate reductions in performance comparatively. Flax has substantially lower mechanical properties but presents a captivating argument regarding sustainability concerns. Kevlar shows signs as strong energy consumption, as expected based on literature, but does raise some implications in sustainability. Aluminium however, despite being inferior remains advantageous considering its sustainability due to its recyclability.

Overall, these findings highlight that no material is completely optimal when regarding performance and sustainability impacts. Instead, it proves how material selection should be based on specific applications, however, there is increasing potential for hybrid or bio composites that will help to reduce environmental impacts without performance compromises.

Lastly, recommendations are mentioned for concerns of adopting recycled or bio/natural fibre composites in appropriate applications, along with recommending further improvements to the tensile testing itself on how to ensure further confidence and accuracy in results.

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1. Introduction

The automotive and motorsport industries are undergoing significant material transition driven by the dual demands of performance and environmental impact. Composite materials remain central to this shift due to their high strength-to-weight ratios, enabling lightweight design and reduced emissions. However, increasing regulatory pressure from organisations such as the FIA, when in context of motorsport applications and European Union, when regarding general automotive industries across Europe and the UK, has placed greater scrutiny on their environmental credentials.

This report investigates a range of composite materials relevant to these sectors, comparing synthetic, natural, and recycled fibre systems in terms of performance and sustainability. Materials studied include aluminium (as a benchmark), carbon fibre (woven and non-woven), carbon/epoxy, Kevlar, and flax (woven and non-woven). Experimental tensile testing was conducted, with results validated against manufacturer datasheets and published literature. In parallel, a lifecycle assessment evaluates the environmental impact of each material. The report concludes with evidence-based recommendations on material selection, considering the feasibility of adopting lower-impact composites without compromising structural performance.

2. Literature review

2.1 Composite Materials in Automotive and Motorsport Applications

Composites have become a fundamental consideration regarding the engineering to high performance vehicles, this is driven by the desire for reduced masses without compromising the overall structural integrity of a component. Fan and Njuguna (2016) note that fibre reinforced polymer (FRP) composites offer a significant amount of weight saving over that of metallic structures, with carbon fibre reinforced polymers (CFRPs) achieving tensile strengths of up to five times more than structural steel. Specifically considering motorsport, the adoption of carbon fibre usage for components can be dated back to the 1980s in Formula 1, where the use of it in the construction of the monocoque chassis represented a huge change in both safety and performance. Since, the usage of composite materials has trickled down far and wide across motorsport categories and even into the regular automotive use case, where lightweight aims is now a central strategy for reducing vehicle emissions that are in line with EU CO2 targets (Mallick, 2007).

2.2 Carbon Fibre Reinforced Polymers

CFRPs are characterised by their exemplary performance regarding the stiffness, strength to weight ratio and fatigue resistance. Woven carbon fibres, such as the twill 2x2 weave, are seen commonly used in structural panels and aerodynamic components because of their balanced mechanical properties and formability particularly with

complex geometries. Twill weave features an interlacing pattern that reduces fibre crimp when compared to plain weave, this results in improved tensile and flexural performance (*Mallick, 2007*). Typical high tenacity carbon filaments, such as Pyrofil TR series from Mitsubishi Rayon, exhibits tensile strength in the range of 4120-5300MPa and tensile moduli of 234-250GPa at fibre level (*Mitsubishi Rayon, 2013*). However, it should be known that laminate properties are significantly lower due to volume fraction, resin properties and lay up configuration which generates a notable distinction that is critical when interpreting results.

2.3 Recycled Carbon Fibre

Within the industry there is a growing awareness of waste that is generated by composites, and this has prompted increased research into materials such as recycled carbon fibre (rCF). Pyrolysis is, as it stands the most commercially viable method, with studies demonstrating tensile strength retention of over 90% in recovered fibres when compared to virgin equivalents (*Butenegro et al., 2021*). Non-woven formats represent a practical application of rCF, where haphazard fibre orientations produce quasi isotropic mechanical behaviours, which is useful for components that require multidirectional load resistance. Whilst rCF composites offer lower mechanical properties than that of virgin woven composites, they do offer for a much reduced environmental footprint and a representation of an important step towards recirculation in the composite supply chain (*Pakdel et al., 2021*). Critically, the randomness of the short fibre architecture of non-woven materials means that a direct comparison with woven structures must account for inherent differences in the efficiency of fibre alignment.

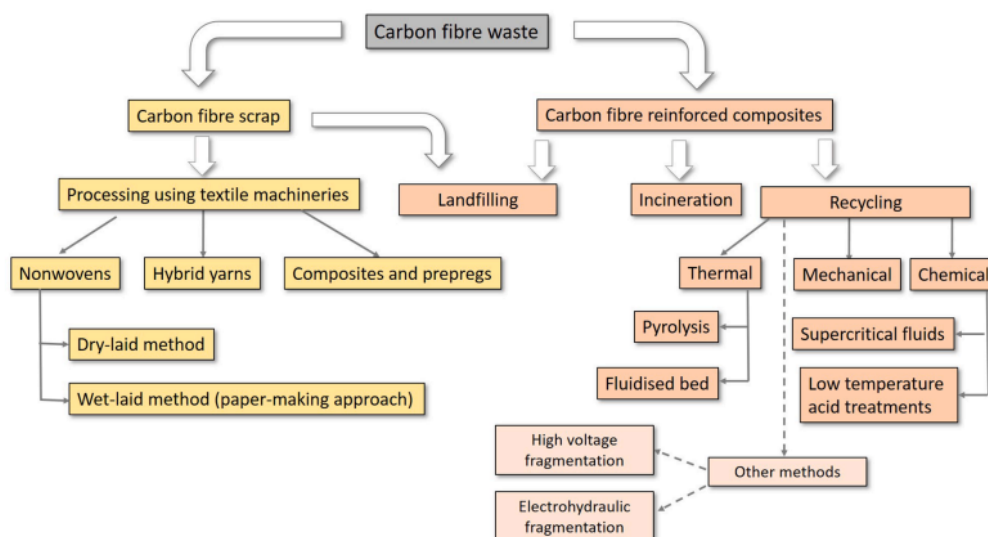


Figure 1 CFRC waste and dry CF scrap management routes (*Pakdel et al., 2021*)

2.4 Natural Fibre Composites

A key point of research has been natural fibre composites especially those reinforced with flax, due to their use as alternatives to glass and carbon fibre in semi structural

applications. Flax fibre is primarily comprised of cellulose, hemicellulose and lignin, and features fibre level tensile strengths of 500-1500MPa and a young's modulus of 60-80GPa, comparable to E-Glass on a specific basis (*Bourmaud et al., 2018*). However, when in composite form laminate strengths are seen to be lower due to poor interfacial bonding between natural fibres and hydrophobic epoxy matrices, along with the variability associated with natural materials. Woven flax architectures exhibit superior mechanical performance compared to non-woven, owing to more efficiency in load transfer facilitated by continuous fibre yarns (*Gowda et al., 2022*). FibriMat F300 a non-woven material, utilises shorter fibres and achieve lower volume fractions during infusion, resulting in reduced tensile strength and modulus, yet offer conformability and lower cost.

Natural fibres have limitations however, such as moisture sensitivity. This is due to the flax fibre being hydrophilic and absorbing significant amounts of water, leading to the degradation of the fibre and affecting the adhesion, this results in a further reduction of performance.

2.5 Kevlar Fibre

Kevlar is known as an aramid fibre, a para-aramid synthetic fibre distinguished by their strength, energy absorption and low density being around $\sim 1.44\text{g/cm}^3$. These properties make them well suited for crash structures, ballistic protection and components subject to significant dynamic loading (*Mallick, 2007*). Kevlar composites are difficult to machine and exhibit poor compressive strength relative to their tensile strength, a known limitation. When used in hybrid combinations with flax or bio resin, Kevlar contributes impact protection as flax provides damping and sustainability benefits, a combination explored by Gowda et al (2022), whose work on hybrid materials demonstrates flexural strengths exceeding 370MPa.

2.6 Resin Systems

Epoxy resins are the dominant matrix material in high performance manufacturing, as it's valued for low cure shrinkage, excellent adhesion, chemical resistance and mechanical properties. Infusion grade epoxies are formulated using ultra-low viscosity to facilitate fibre wet out under vacuum pressure. Bio derived epoxy systems represent an emerging class of matrix materials where petroleum based precursors are partially replaced with plant based equivalents. Epichlorohydrin a key part of epoxy chemistry can be synthesised using glycerol, a renewable byproduct of biodiesel, in place of petroleum based propylene (*Easy Composites, 2024*) Bio epoxy systems demonstrate mechanical properties comparable to their counterparts, however, their glass transition temperature is typically lower, hinting at limited use when in elevated temperature environments.

2.7 Tensile Testing of Composite Materials

The characterisation of a composite's mechanical properties is done through tensile testing and is governed by ISO 527-4:2021, which specifies the test conditions for iso, and orthotropic fibre reinforced plastic composites. 'Dog bone' like shaped specimens are loaded uniaxial tension at a controlled crosshead displacement rate, which is typically 1-2mm/min for modulus determination and up to 5mm/min for strength measurement. The tensile strength is calculated by dividing the max load at failure by the cross sectional area of the gauge section, whereas the young's modulus is derived from the linear region of the stress-strain curve (ISO, 2021). Validation of experimental data is typically established by comparing to manufacturer datasheets in order to establish reliability of results.



Figure 2 Example of tensile test specimens

3. Analysis of Sustainability and Environmental Impact

3.1 Lifecycle Assessment Framework

Meaningful analysis of sustainability when regarding composite materials, it must extend beyond manufacturing phase carbon accounting to encompass the full lifecycle, from raw material extraction through in service use to end of life management. The ISO 14044 standard provides the internationally recognised framework for lifecycle assessments, defined of four phases, goal and scope definition, life cycle inventory, impact assessment and interpretation (ISO, 2006). This section applies to the 'cradle to grave' LCA perspective to evaluate the environmental impact of the six composites investigated. A degree of uncertainty should be carried due to varying LCA data for composites between studies.

3.2 Legislative Context and Industry Drivers

The regulatory landscape increasingly pressures the automotive and motorsport industry sectors to address material sustainability. In July 2023, European commissioners proposed a regulation that merged the end of life directive and the 3R type approval directive into one, which would cover the complete vehicle lifecycle, whereby mandatory targets were required, that new vehicles contain at least 25% plastic content that is sourced from recycled materials. When enacted, this legislation aims to deliver a reduction of 12.3 million tonnes annually of CO₂ or equivalent by 2035, furthermore, improving recycling of 5.4 million tonnes of material annually.

Regarding motorsport specifically, the FIA has a 'sustainability strategy 2030' and the WECs push for the Le Mans Hydrogen project reflect the wide recognition of environmental credential regarding materials and powertrains improving in parallel. Formula 1 also features a sustainability strategy to commit to a net zero carbon across the sport by 2030, encompassing supply chain and material decisions (*FIA, 2021*), creating both an incentive ad market for the adoption of recycled carbon fibre, bio based resins and natural fibre composites.

3.3 Standard Carbon Fibre

Carbon fibre, represented by twill 3K woven CFRP in this study, has one of the highest energy and carbon footprints among the materials analysed. Its production is highly energy intensive, requiring sustained high temperatures during oxidation and carbonisation. Lifecycle assessments estimate emissions of 13-34.1 kg CO₂ per kg of fibre and energy consumption of 262-498 MJ/kg, depending on manufacturing scale and energy sources. Additionally, the carbonisation process generates toxic byproducts such as hydrogen cyanide and ammonia, environmental impacts that are often underrepresented in LCA studies focused primarily on greenhouse gas emissions (Butenegro et al., 2021).

3.4 Flax Fibre Composites

The flax fibres used in woven and non-woven formats present one of the more outstanding environmental arguments. Materials such as FlaxDry BL200 and FibriMat F300 source 100% of the European flax from EcoTechnilin, this holds significance due to the carbon footprint of European natural fibres being ~900 kgCO₂, especially noteworthy when compared to the 1700-2500kg CO₂ for glass fibres. Crucially, flax fibres isolate atmospheric CO₂ during the cultivation through photosynthesis, since they are plant based. This contributes to the offset of production emissions, which is absent when considering synthetic fibres (*Lopez Arraiza et al., 2025*). LCAs consistently have shown that flax material systems emit significantly less CO₂ compared to glass epoxy equivalents, with published studies such as the one produced by Lopez Araiza et al (2025) detailing a ~47% reduction, these reductions are backed up further by papers

by Georgios Koronis et al (2022) and Arte Seile et al (2022) also explain reductions shown regarding flax epoxy materials.

At the end of life, flax reinforced thermoset composites behold similar challenges of all thermoset systems. However, when paired with biopolymer matrices, composting and biodegradation can become achievable, this approach is currently being investigated in advanced bio composite research (*Bourmaud et al., 2021*).

3.5 Kevlar Sustainability

Kevlar presents complex sustainability profiles. The production of the material involves energy intensive polymerisation processes, where the use of harsh chemical solvents like sulfuric acid for example, introduces human and ecotoxicity challenges (Mallick, 2007). Aramid fibres are not readily biodegradable, therefore, feature end of life challenges. However, the energy absorption of Kevlar and its uses as a composite present an argument for its lifecycle due to its longevity in components and a reduced replacement frequency.

3.6 Sustainability of Aluminium

Aluminium has been used in this study to be used as the conventional benchmark in the study. Aluminium production is energy intensive, featuring an average global warming potential of ~8-17kg CO₂ depending on electricity sources used in smelting (*Hammond and Jones, 2011*). However, aluminium has an established and efficient recycling route, where recycled aluminium required approximately 5% of the energy that normal production does. The EUs end of life regulations specifically highlights it as a material where closed loop recycling targets may be introduced, reflecting its recyclability. Contextually to this study aluminium features the best end of life recyclability of all tested materials tested, which is a significant consideration.

4. Experimental Testing

4.1 Tensile Testing Methodology

The tensile test conducted remained in line with the correct health and safety, in the lab. The process remained fairly basic, where each material had been tested under the same circumstances in the tensile testing machine and results had been recorded and saved into its own file. The materials themselves were all of the same or at least similar sizes in the 'dog bone' styled shape as mentioned in the literature review. Analysis was then conducted and validated against other groups and papers.



Figure 3 showcasing an example of a specimen in the tensile test machine

4.2 Tensile Test Analysis

4.2.1 Stress-Strain and UTS Analysis

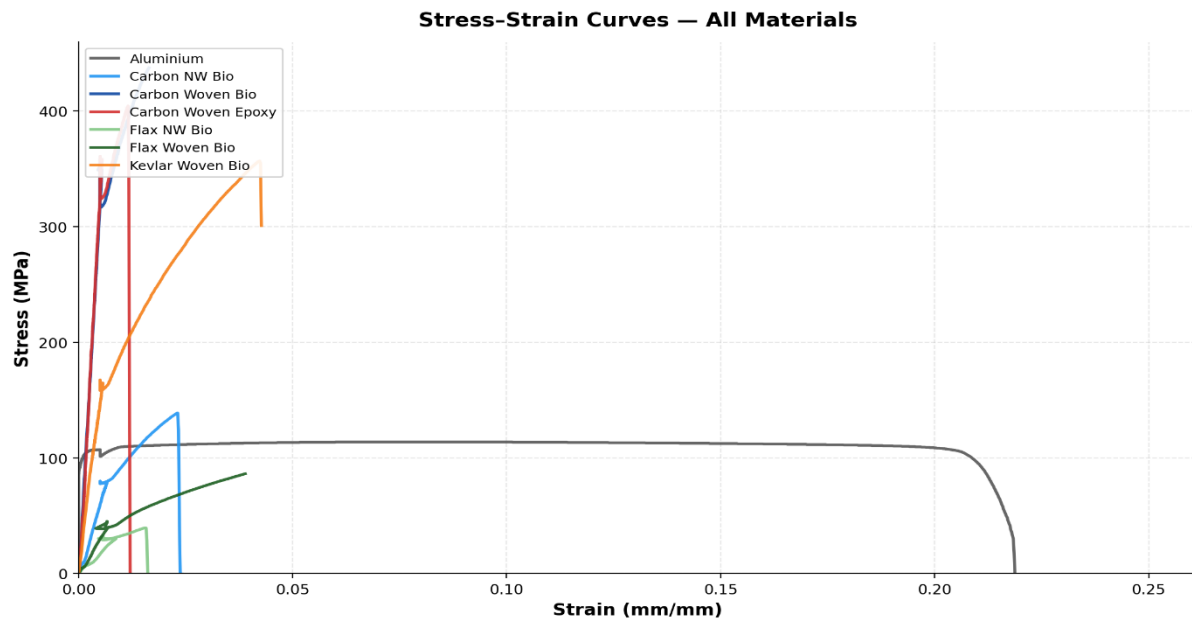


Figure 4 Stress / Strain graph of all tested materials

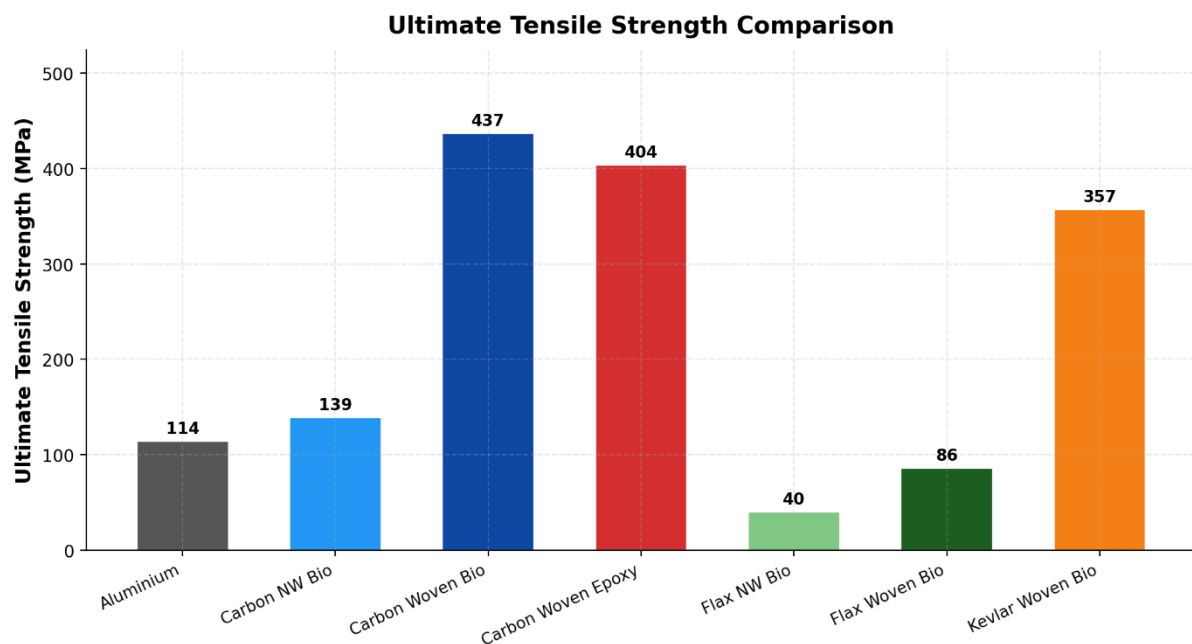


Figure 5 UTS values of each tested material specimen

The stress-strain behaviour identified within Figure 3 is seemingly consistent with the expected performance of these materials. Carbon fibre composites exhibit high stiffness values with low strain to failure of ~1-2% and high UTS, with the woven and epoxy variations reaching 437MPa and 404MPa respectively. These values, however, are seen as higher than 316.94MPa that is reported by Ion Spinu et al (2024) for bidirectional woven carbon laminates, however, seemingly align closer to the 432MPa examined by B.A. Praveena et al (2020), who conducted a study using higher fibre volume fraction

and vacuum bag moulding. This information suggests that the results are more attributable to differentiations lay up and fibre content, a well established driver to composite performance. However, the non-woven bio composite is displaying much lower strengths of 139MPa, this is consistent with understandings from literature that note a reduction in mechanical properties in non-woven fibres, this is further highlighted by Eshan Pakdel et al (2021) and supported by manufacturer datasheets.

Flax based composites, however, display a significance in lower stiffness and strength but signs of greater ductility, which is typical of natural fibres. The woven variation demonstrating 86MPa, which slightly surpass results precured by S.A. Hawkins et al (2020), this can be put down to differences in architecture or volume fractions, particularly when observing the FlaxDry BL200 specimen. An investigation by Maria Rosaria Ricciardi (2024), validates for this as they used the same type of material with a bio epoxy based system and discovered comparative mechanical performance and negligible differences in bio based and conventional resin approaches. The results non-woven flax falls within the 37-44MPa range reported by EcoTechnilin datasheets, as from the test it results in around 40MPa, reinforcing reliability of the results displayed. The Kevlar composite display immediate behaviour, reporting 357MPa, which is higher than the reported 233Mpa by Sylwia Czlonka et al (2020), however, is comfortably within the 280-380MPa range that S. Sathishkumar et al (2021), again suggests that architecture and fibre volume fractions ca be an influencer.

The aluminium specimen displays typical ductile behaviour, with a yield of around 114MPa and a large strain to failure, this aligns with several published low strength or annealed aluminium, typically seen around 90-110MPa, rather than alloys like 6061 which is seen at around 270MPa.

Overall, the validity of the results when compared to published literature, is demonstrated to be fairly consistent regarding established ranges with reasoned differentiations.

4.2.2 Youngs Modulus Analysis

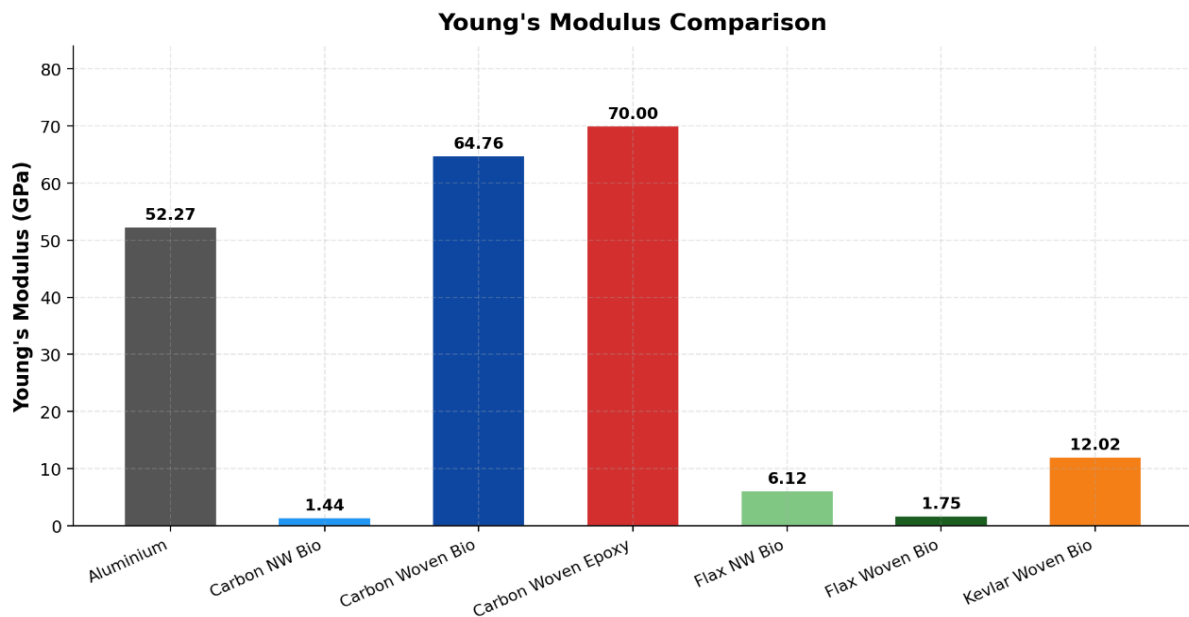


Figure 6 Youngs Modulus of Each Material specimen

Carbon woven epoxy recorded the highest value at 70GPa, then carbon woven closely follows with 64.76GPa, these both exceed aluminium's 52.27GPa, this aligns with published woven CFRP laminate values of 40-70GPa (*Spinu et al., 2024*). Carbon non-woven depicts what's to be believed as anomalous result due to the low modulus despite the UTS being 139MPa, this is perceived as an issue in the test itself, as datasheets like from Easy Composites (2024) report a modulus of 25-35GPa at 30% fibre fraction. Flax specimens display 6.12GPa and 1.75GPa for woven and nonwoven respectively, broadly aligning with work by Dhakal and sain (2020) where figures of 4.67GPa for vacuum infused flax epoxies was examined. Kevlar returns a value of 12.02GPa, reflecting the stiffness characteristic of such aramid fibres (Mallick, 2007).

4.2.3 Specific Strength Comparison

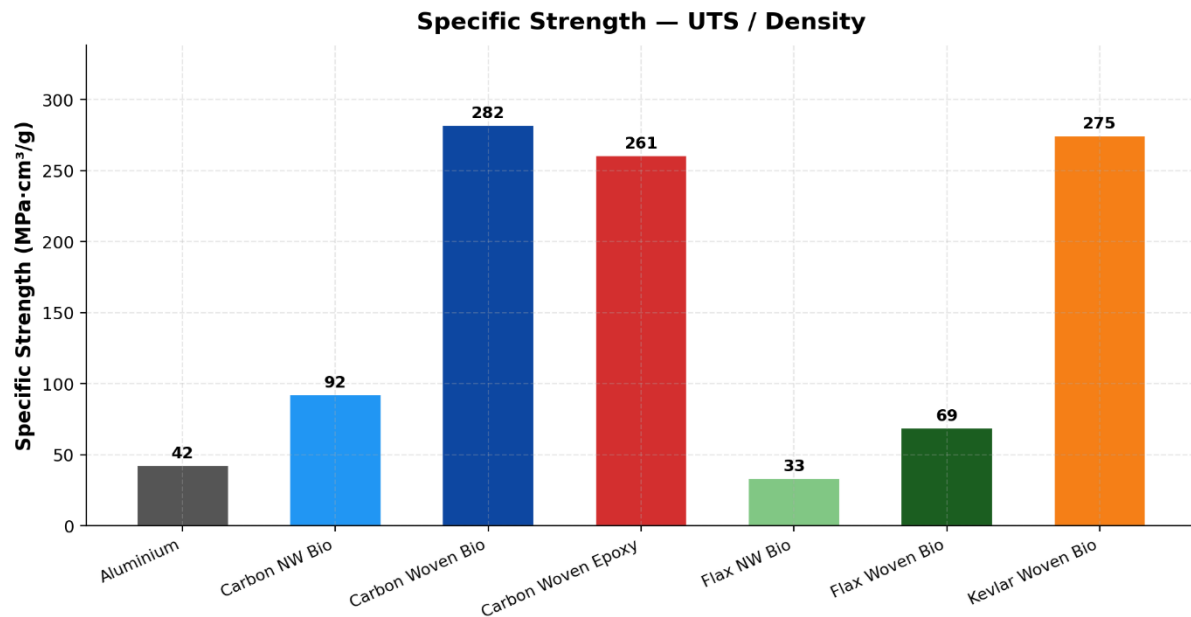


Figure 7 Specific Strength Comparison Graph

The specific strength is the sum of the UTS divided by material density, this quantifies how much strength a material delivers per unit of mass. Carbon woven achieved the highest again followed by Kevlar and carbon epoxy, which all dramatically outperform aluminium at 42MPa·cm³/g, which quantifies justification for use in more performance based structures (Fan and Njuguna, 2016) due to its exceptional specific strength and stiffness when compared to regular metals as discussed by Balla et al (2022). Recycled carbon non-woven bio achieves more than double aluminium, suggesting rCF based materials offer for credible sustainable alternatives. Flax recorded 69 and 33 MPa·cm³/g for woven and non-woven respectively, the woven format exceeding aluminium on a specific basis despite falling short of carbon and Kevlar, consistent with Dhakal and Sain (2020).

4.2.4 Comparison of Stress-Strain of Fibre Types

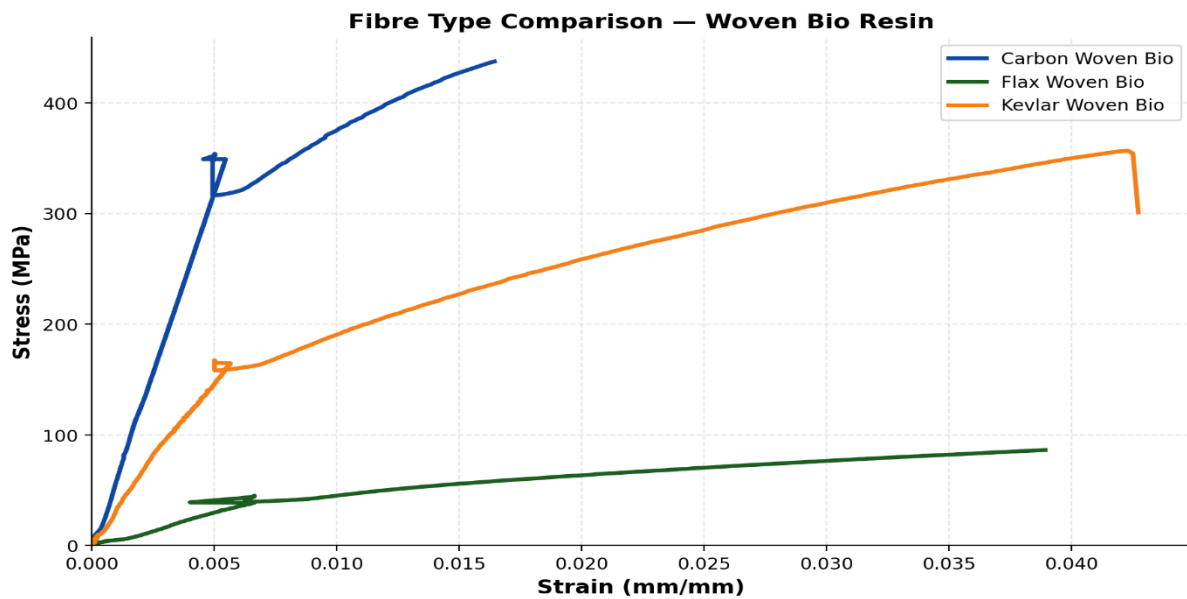


Figure 8 Comparison of fibres stress-strain graph

Figure 9 isolates the fibre types, by displaying the stress-strain graph. Carbon exhibits a steep linear elastic response before an abrupt brittle fracture, this is a characteristic of fibre dominated failures in epoxy laminates. The visible load decrease suggests damage mechanisms like matrix cracking, behaviour reported by the likes of Kollar and Springer (2003). Similar curve responses have been observed by Hallet et al (2009), where they mention that damage accumulation like such, precedes catastrophic fibre failure. Kevlar displays a nonlinear progression, reflective of the energy absorption seen in aramid fibres. Flax displays bilinear response a characteristic also documented by Ricciardi et al (2024), initial elastic region is transitioned at around 35MPa into a low stiffness region as microcracking progresses, ultimately leading to failure. These curves illustrate that the selection of fibres is crucial and can determine their usage, with carbon suited to stiffness critical structures, Kevlar to energy absorption, and flax to lower-load sustainable applications.

4.3 Material Fracture analysis



Figure 9 Post Tensile test fractures of each material tested

The Kevlar (bottom left) displays delamination and fibre pull out more than a fracture, atypical characteristic of aramid composites. This is where the interfacial bond strength causes failure through progressive fibre debonding rather than a brittle fracture, this is consistent with what is displayed in figure 8 and further documented by Czlonka et al (2020).

Carbon woven bio (bottom middle) and woven epoxy (top middle) display sharp, clean fractures with little fibre pull out, which aligns with the stress-strain pattern seen, detailing the brittle fracture characteristic. The near identical fracture appearance between bio and epoxy resin specimens supports the finding that fibre architecture, rather than resin, is the dominant determinant of failure mode in woven CFRP (*Spinu et al., 2024*). Whereas non-woven is more jagged, representing crack propagation through randomly oriented short fibres, the fracture formation contributes to modest energy absorption seen in short fibre composites (*Pakdel et al., 2021*).

Aluminium shows visible plastic deformation, with slight reduction in cross sectional area which is indicative of ductile failure through plastic deformation before fracturing. This is contrasting against the other specimens, reinforcing the behaviour observed across the material stress-strain data in Figure 4.

5. Recommendations

Based on the findings, woven CFRPs remain the recommended material for application in motorsport components, with bio epoxy preferred over standard epoxy, due to the comparable UTS (437 MPa against 404MPa), and for its more sustainable approach, though the lower 'T_g' should be considered for thermally demanding areas. Flax bio composite is a good alternative for use in non-structural based bodywork and panelling, this is a consideration supported by BMW Motorsports utilisation in Formula E and GT4, and furthermore McLaren Racings 2023 rCF trial, demonstrating the adoption of recycled carbon fibre, saving over 32,000 tonnes of CO₂ annually (McLaren Racing 2023; BMW Press, 2023). Recycled carbon can be used for semi structural bulking applications backed up through its specific strength value.

For future testing, further repeats of material testing can be done in order to gain further reliability (~5 times), as due to time constraints the 2 times limits confidence in results. Investigations into flax fibre surface treatments could improve interfacial adhesion, identified as a limiting factor in the fractographic analysis, and thereby enhance tensile performance. Conditioning specimens for moisture would also provide more representative results for exterior automotive applications, given the hydrophilic nature of flax fibres. In the longer term, thermoplastic bio based matrices should be explored to address recyclability limitations associated with thermoset epoxy systems (Alshahrani et al., 2024).

6. Conclusion

This study has established that overall wove carbon composites provide the higher mechanical performance across all metrics, with the bio achieve a UTS of 437MPa and a specific strength of 282MPa.cm³/g, whilst maintaining comparable properties to the regular epoxy counterpart, confirming bio resin as a feasible low impact substitute (see Figure 13). Natural fibre composites, whilst mechanically inferior, provide credible sustainable alternatives for non-structural uses, supported by industry implementation. Cross group comparisons highlighted the sensitivity regarding composite testing, underlining the use for standardising manufacturing processes in future (see Appendix 1). Collectively, the findings support hybrid material usage, retaining carbon fibre where demanded whilst substituting natural and recycled fibres elsewhere.

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Appendix 1. Analysis of Data from Another Group and Comparisons

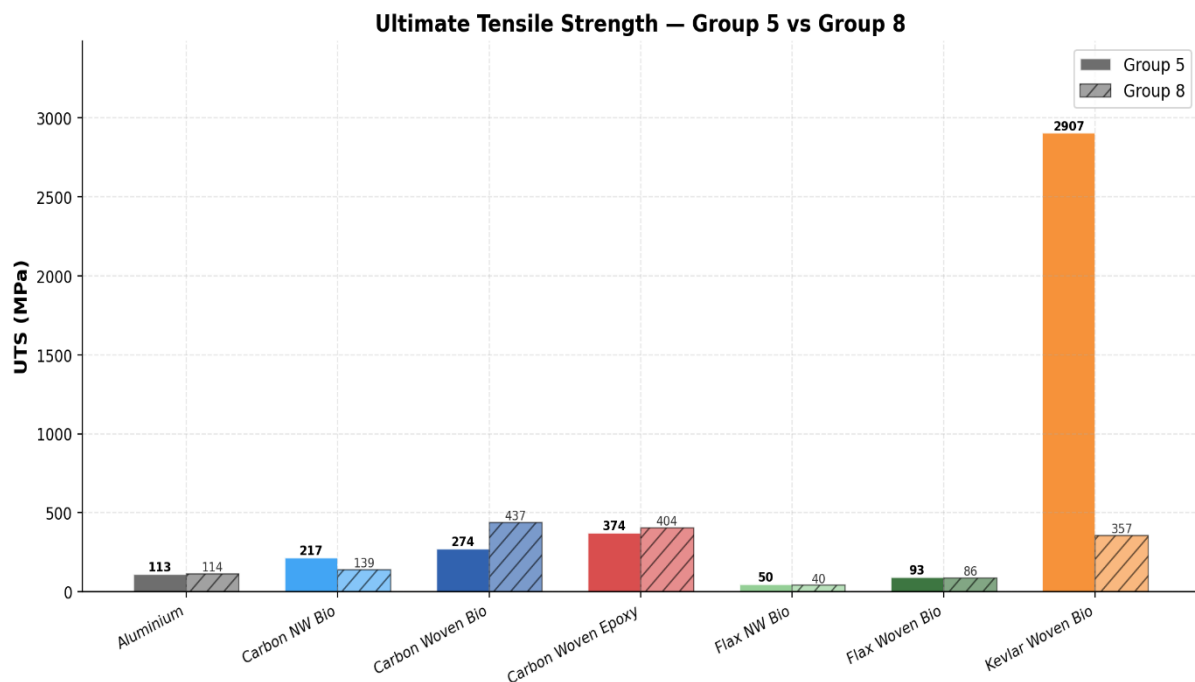


Figure 10 Group 5 vs Group 8(personal group) UTS values

This graph depicts a comparison between group 8 which is the personal group the test had been completed in, and group 5. Overall, this graph displays results reasonably consistent to each other across both groups especially when regarding aluminium and flax woven bio, this allows for fairly validating results and therefore reflecting reasonable confidence in the results taken. However, group 5 has an obvious anomaly regarding Kevlar, displaying a UTS of 2,907MPa, which is not possible for woven Kevlar at these fibre volume fractions and shows an error in their test results.

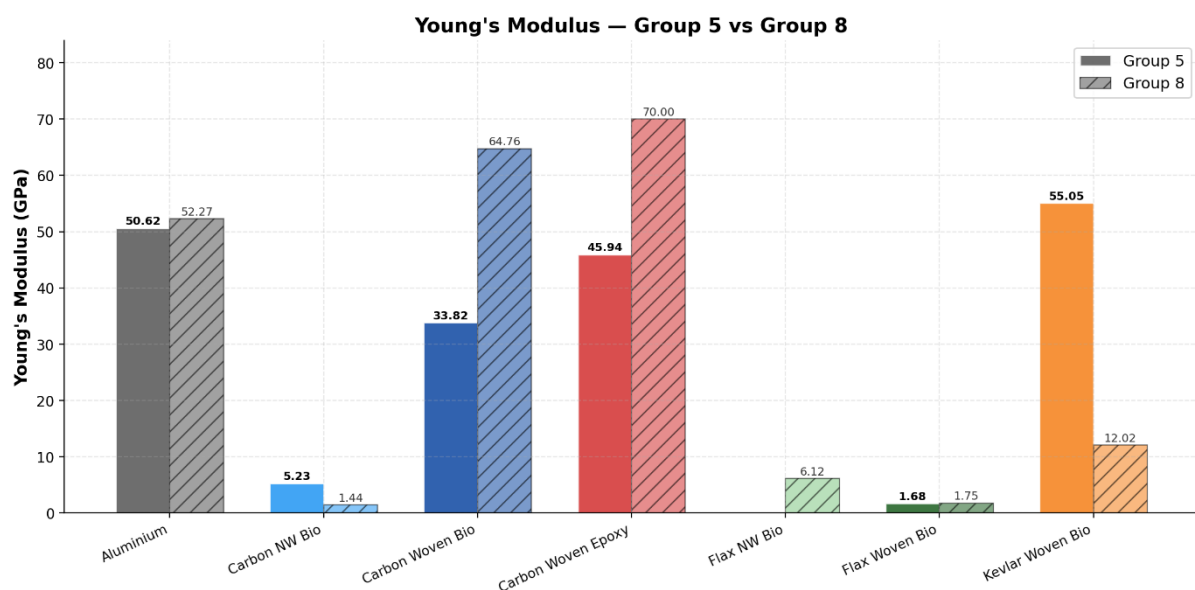


Figure 11 Young's Modulus of both groups

The same pattern tends to emerge when looking at the young's modulus with aluminium and flax woven displaying similar results yet again. However, largely overall there are varying ranges of differentiations in results. Despite this, both sets of data account for woven carbon systems having consistent patterns, where carbon woven epoxy is stiffer than the woven bio counterpart, detailing that the trend is repeatable across groups. The differences in absolute value, may be down to extensometer performance at the time or slight variations in specimens.

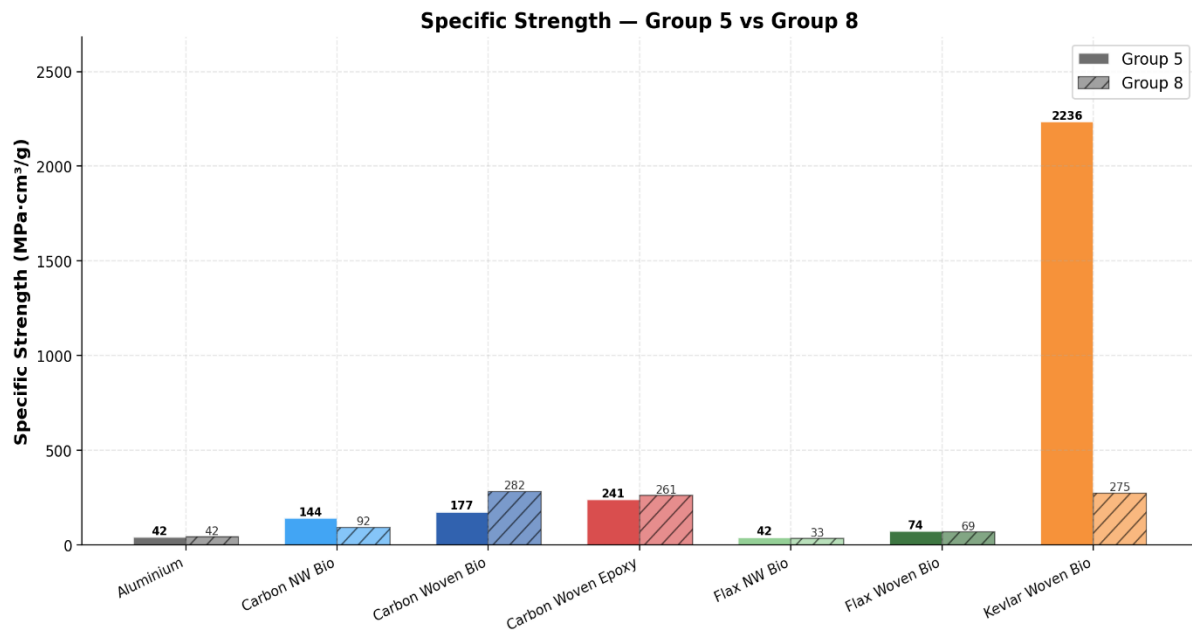


Figure 12 Specific strength comparison

Data from both groups displays that there is confirmation that the woven composites outperform aluminium, this consistency across both of the groups further strengthens the argument for composite adoptions in lightweight applications.

Table 1 Table of raw data from both groups

Material	Group 5 UTS (Mpa)	Group 8 UTS (Mpa)	Diff (%)	G5 E (Gpa)	G8 E (Gpa)
Aluminium	113	114	-0.9	50.62	52.27
Carbon NW Bio	217	139	56.1	5.23	1.44
Carbon W Bio	274	437	-37.3	33.82	64.76
Carbon W Epoxy	374	404	-7.4	45.94	70
Flax NW Bio	50	40	25		6.12
Flax W Bio	93	86	8.1	1.68	1.75
Kevlar W Bio	2907	357	714.3	55.05	12.02

Appendix 2. Additional Graphs Group 8 Data

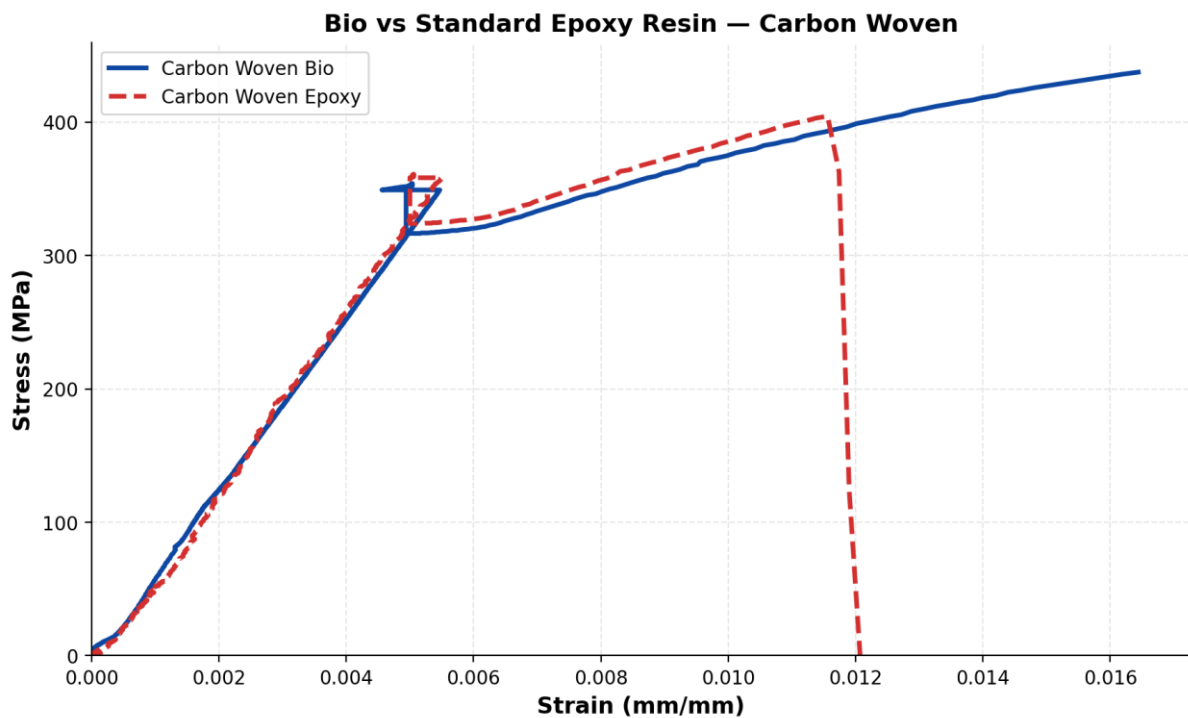


Figure 13 Resin comparison of carbon woven materials

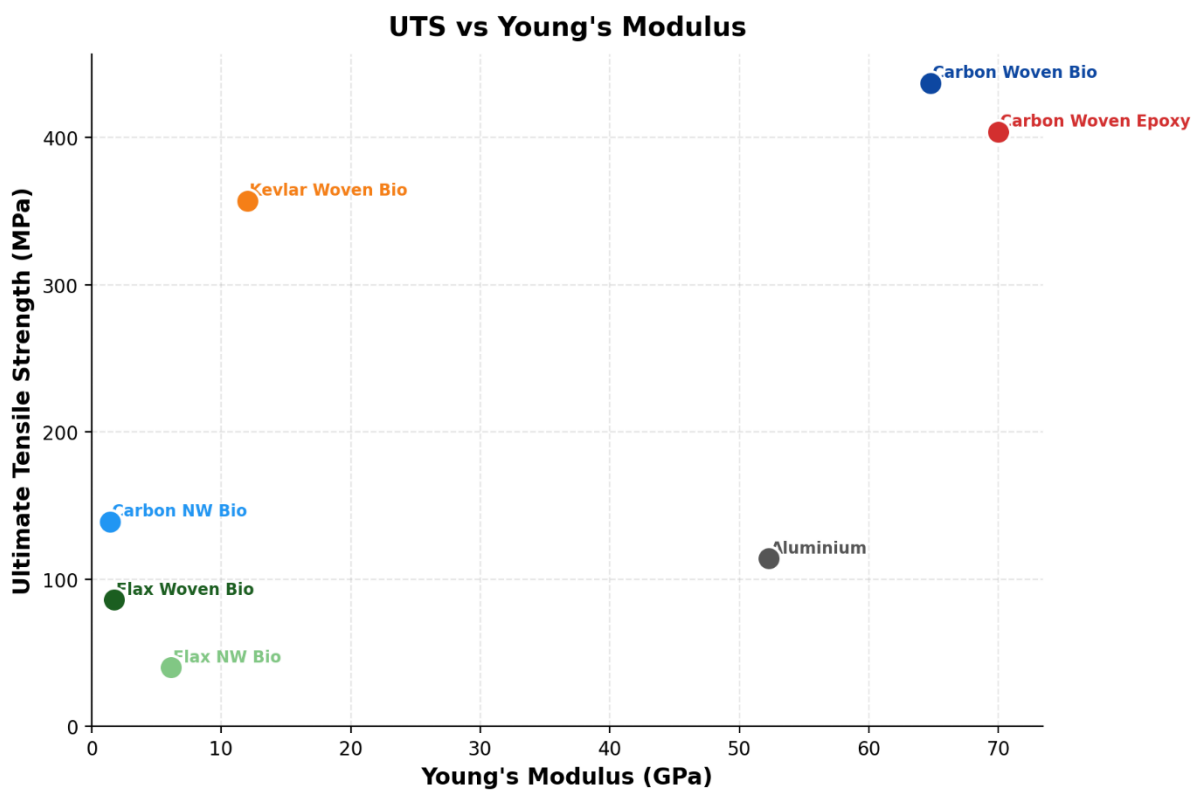


Figure 14 UTS vs Modulus Graph

The UTS vs Young's modulus graph in Figure 14 helps to visualise both of these properties at the same time, its usefulness comes down to depicting which materials

are strong and stiff and likewise, essentially another way of showing mechanical performance. This would be a big determiner in material selection, displaying what the more ideal materials are for high performance use.

As shown, the carbon woven materials are dominant above the rest as they have a high UTS and a high young's modulus. Kevlar displays an interesting argument, where it has a high strength but low young's modulus, a characteristic known for materials such as Kevlar used for energy absorption. Aluminium sits relatively low on the UTS axis but displays a reasonably high young's modulus, but being behind the carbon woven materials, this justifies the argument for composite substitution. Flax materials being around in the bottom left corner represent their limitations when used in structural applications, therefore hinting its use case is elsewhere.

Tensile Properties Summary Dashboard

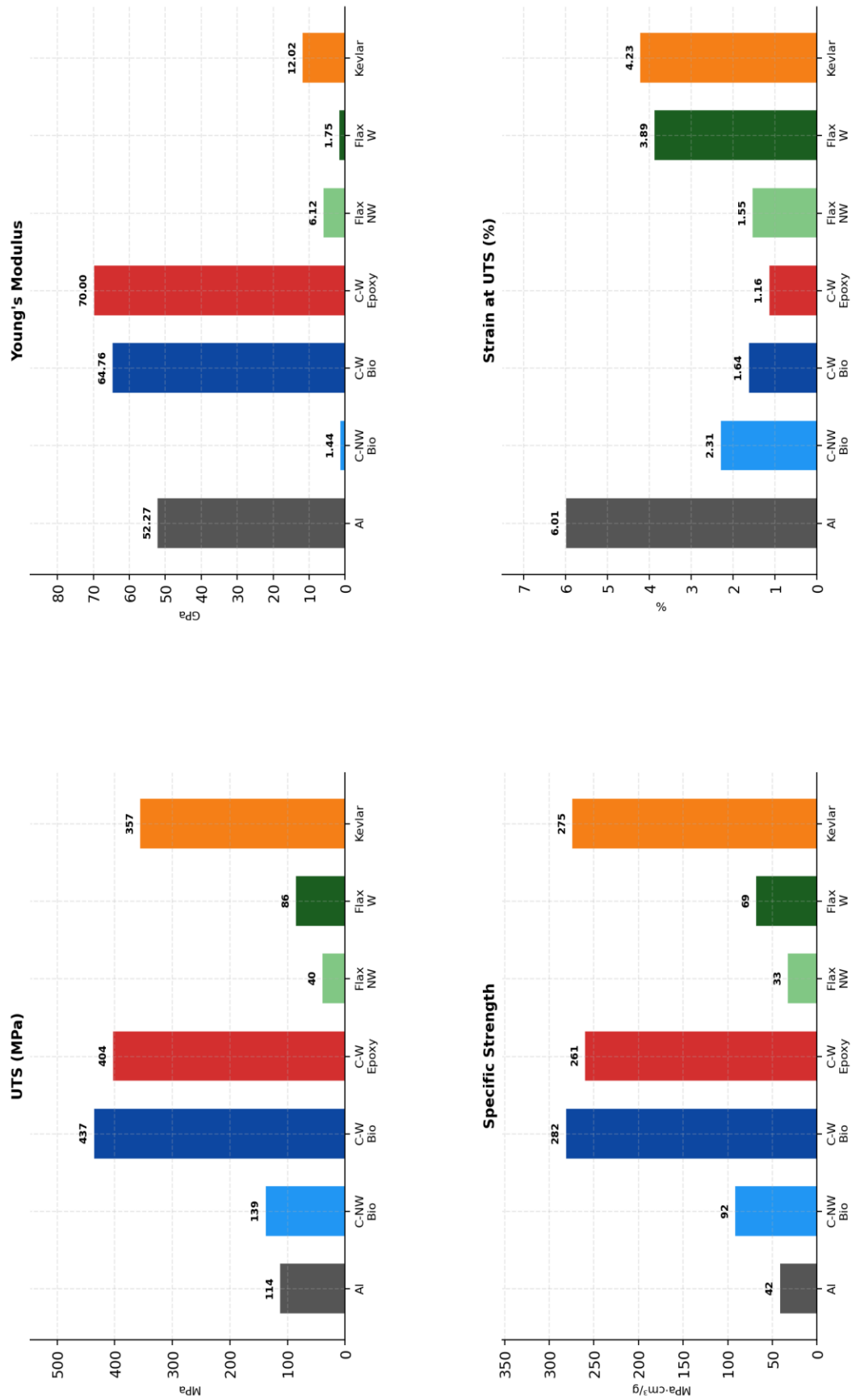


Figure 15 Collection of all data gathered from Group 8

