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Automotive Materials & Sustainability

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1 Introduction

The use of composite materials in the automotive industry is becoming increasingly common in modern vehicle manufacture. Their increased use has allowed road vehicles to become lighter while still maintaining the strength and structural performance required for safe and effective operation. This can improve overall vehicle efficiency, as well as braking and handling performance. Materials such as carbon fibre and natural-fibre composites are now used across a wide range of applications, including structural components, body panels and safety-related parts.

Alongside these performance advantages, sustainability has become a more important factor in material selection. Although many composite materials provide clear mechanical benefits, some, such as carbon fibre, are energy intensive to produce and are derived from non-renewable sources. This has placed greater emphasis on the full life cycle of automotive materials, with increasing attention being paid not only to exhaust emissions, but also to wider environmental impacts such as tyre and brake particle pollution. As vehicle mass has generally increased over time, these non-exhaust emissions have become a more significant concern for the automotive industry.

By comparing how different composite materials perform against the metallic materials they are intended to replace, it is possible to assess the most suitable use cases and determine whether they are mechanically, environmentally and economically fit for purpose. This report therefore evaluates a range of composite materials through tensile testing and sustainability analysis to assess their suitability for automotive and motorsport applications.

2 Literature Review

Composite materials have become increasingly important in automotive and motorsport engineering because they allow significant mass reduction without unacceptable losses in structural performance. As McBeath (2009) notes, fibrous materials offer some of the best mechanical properties of any structural material when used correctly. However, fibres alone are not structurally useful, as individual strands are flexible and unable to maintain shape or transfer load efficiently. By combining the fibres with a matrix material, typically a resin, the reinforcement can be held in place, loads can be distributed more effectively, and the full mechanical potential of the fibre architecture can be utilised. This ability to combine low density with high strength and stiffness has made composite materials particularly attractive in applications where structural efficiency is critical.

Material selection within the automotive industry has continued to evolve in response to advances in technology, changes in manufacturing methods and increasing performance demands. In both automotive and motorsport applications, the need for lightweight structures has encouraged the wider adoption of composites as alternatives to conventional metallic materials. More recently, additive manufacturing has further accelerated interest in polymer and composite systems because it allows the production of complex geometries that would be more difficult or less economical to manufacture using traditional subtractive methods. In addition, 3D printing can reduce material waste, improve prototyping speed and increase design flexibility across a range of engineering applications (Gebrehiwet et al., 2023).

Among the materials used in automotive and motorsport engineering, carbon fibre composites remain the main high-performance option because of their high strength and stiffness at low weight. Kevlar is also used where high tensile strength and toughness are important, although it is generally less stiff than carbon fibre. Natural-fibre composites such as flax are becoming more attractive as lower-impact alternatives, but their mechanical performance is usually lower than synthetic fibre systems. Vignesh et al. (2025) showed that natural-fibre reinforced composites can still provide useful mechanical properties for automotive applications, although their performance depends heavily on the fibre combination and laminate structure. This makes reinforcement type and fibre architecture an important factor when comparing materials for structural use.

3 Sustainability Analysis

The sustainability of engineering materials can no longer be judged just on whether they are renewable or recyclable but must instead be considered across the full lifecycle of the material. In automotive and motorsport applications, this includes raw material extraction, manufacturing energy demand, waste generation, durability in service, repairability and end-of-life disposal. While conventional high-performance composites such as carbon fibre and aramid systems provide excellent mechanical performance, they are often associated with high embodied energy and limited recyclability. In contrast, natural-fibre and bio-based composite systems offer potential environmental advantages through renewability and reduced dependence on synthetic feedstocks, although these benefits may be offset by lower structural performance and reduced durability in demanding applications.

The automotive and motorsport industries are under increasing pressure to improve sustainability while maintaining performance. For example, Euro 7 introduces requirements relating to brake particle emissions, tyre emissions and battery durability. (Belgium : Euro 7: Council adopts new rules on emission limits for cars, vans and trucks²⁰²⁴) This has encouraged the development of lightweight structures, recycled-content materials and bio-based composites, while also placing greater emphasis on designing vehicles for easier disassembly and material recovery at end of life. Under these emerging EU circularity rules, material selection is increasingly influenced by recyclability and recycled content as well as by mechanical performance. However, the adoption of alternative materials still depends on whether they can provide adequate properties for the intended application. Sustainable material selection therefore becomes a compromise between circularity, structural performance, cost and manufacturability. (Circular economy: deal on new EU rules for the automotive sector²⁰²⁵)

Within the present study, carbon fibre composites and Kevlar represent high-performance synthetic material that offer strong mechanical capability, but are generally associated with less favourable sustainability characteristics, particularly in relation to energy-intensive production and more limited end-of-life recovery options. By contrast, flax-based bio-composites offer a potentially more sustainable alternative because the reinforcement is derived from renewable natural fibres, although the lower tensile strength and stiffness typically reported for natural-fibre composites reduce their suitability for highly loaded structural components. Aluminium provides an important comparison material because, although primary aluminium production is highly energy intensive, the material remains widely used due to its durability, established manufacturing routes and strong recyclability as a circular material. (Khan, Hossain et al. 2025)

The recycling of carbon fibre is a high-energy process, because the fibres must be separated from the surrounding resin or epoxy without causing significant damage to the fibres. Current end-of-life routes such as landfill and incineration result in little or no recovery of the original material value. As demand for carbon-fibre composites continues to increase, improved recycling and separation technologies will become increasingly important to reduce waste and support more circular use of high-performance composite materials (Yuan, Li and Teng, 2024)

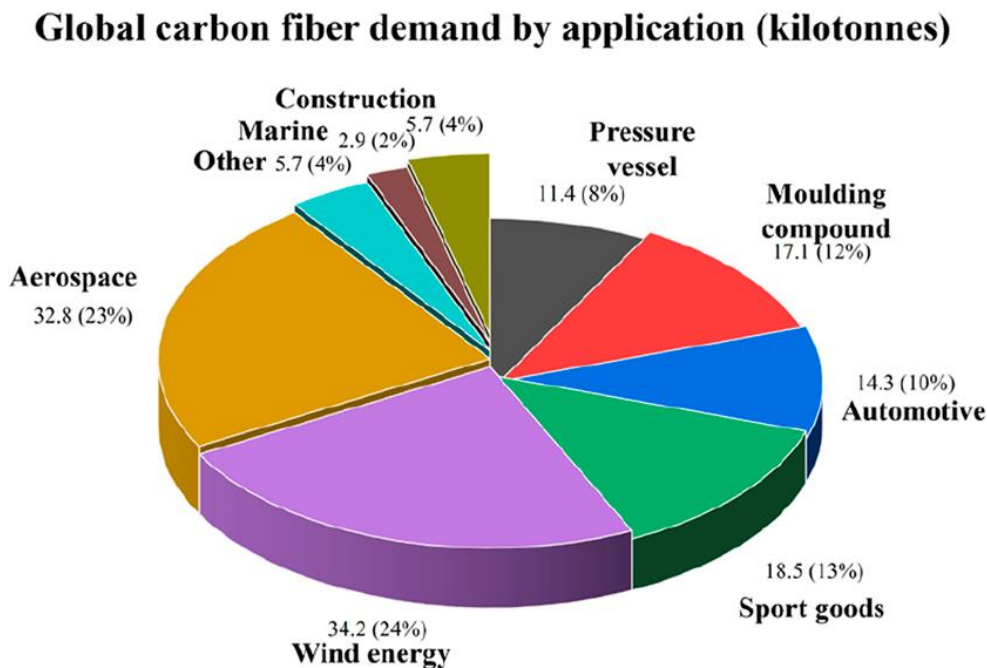


Figure 1- Global carbon fibre demand by application (Yuan M, Li Z and Teng Z)

Overall, the literature suggests that no single material offers both maximum mechanical performance and maximum sustainability. Instead, material choice should be based on the functional demands of the component. High-performance synthetic composites are likely to remain necessary in critical motorsport structures, whereas more sustainable composite systems may be better suited to secondary, interior or non-critical automotive components. This makes experimental comparison essential in determining whether the environmental benefits of alternative materials are sufficient to justify their lower mechanical performance.

4 Experimental Testing / Method

4.1 Samples

The samples used in the testing included both a metallic material and a range of composite materials. Aluminium was used as the control material because it is a homogeneous metal and provides a useful reference for comparison. The composite samples included different fibre types, lay-up patterns and weave structures, allowing the effect of material architecture on strength and stiffness to be assessed.

Table 1-Material Table

<i>Material</i>	<i>Category</i>	<i>Reinforcement type</i>	<i>Matrix type</i>	<i>Architecture</i>	<i>Purpose in study</i>
<i>Aluminium</i>	Metallic reference	None	None	Homogeneous	Benchmark material
<i>Carbon woven bio</i>	Synthetic composite	Carbon fibre	Bio-resin	Woven	High-performance composite with alternative matrix
<i>Carbon woven epoxy</i>	Synthetic composite	Carbon fibre	Epoxy	Woven	High-performance benchmark composite
<i>Carbon non-woven bio</i>	Synthetic composite	Carbon fibre	Bio-resin	Non-woven	Effect of lower fibre organisation
<i>Kevlar</i>	Synthetic composite	Aramid fibre	Polymer matrix	Woven/non-woven as supplied	Tough high-strength comparison
<i>Flax woven bio</i>	Natural-fibre composite	Flax fibre	Bio-resin	Woven	Sustainable alternative
<i>Flax non-woven bio</i>	Natural-fibre composite	Flax fibre	Bio-resin	Non-woven	Sustainable lower-performance alternative

The samples were provided as dog bone suitable for fitting into the tensile testing machine. Some of the composite samples used a biodegradable resin matrix, while others used a conventional epoxy matrix as the binding material.

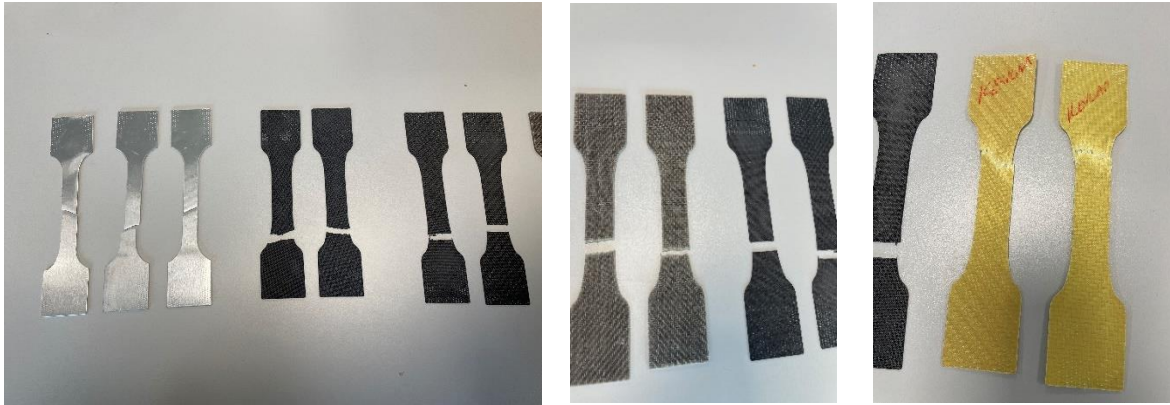


Figure 2- Material samples after tensile testing

4.2 Denison Mayes Group Tensile Test Machine

The Denison Mayes Group tensile testing machine was used to carry out the tensile tests on the prepared specimens. Each sample was clamped securely between two jaws, which applied a uniaxial tensile load until failure occurred. An extensometer was attached to the specimen during the initial stage of the test in order to measure strain accurately within the elastic region. This allowed the elastic response of the material to be recorded and enabled properties such as modulus to be determined. Once the material approached the onset of failure, the extensometer was removed to prevent damage, and the test was continued until complete fracture of the specimen. The machine output a stress–strain response for each test, from which key values such as ultimate tensile strength, proof stress and modulus were obtained.



Figure 3- Denison Mayes tensile testing machine used for specimen testing

5 Results

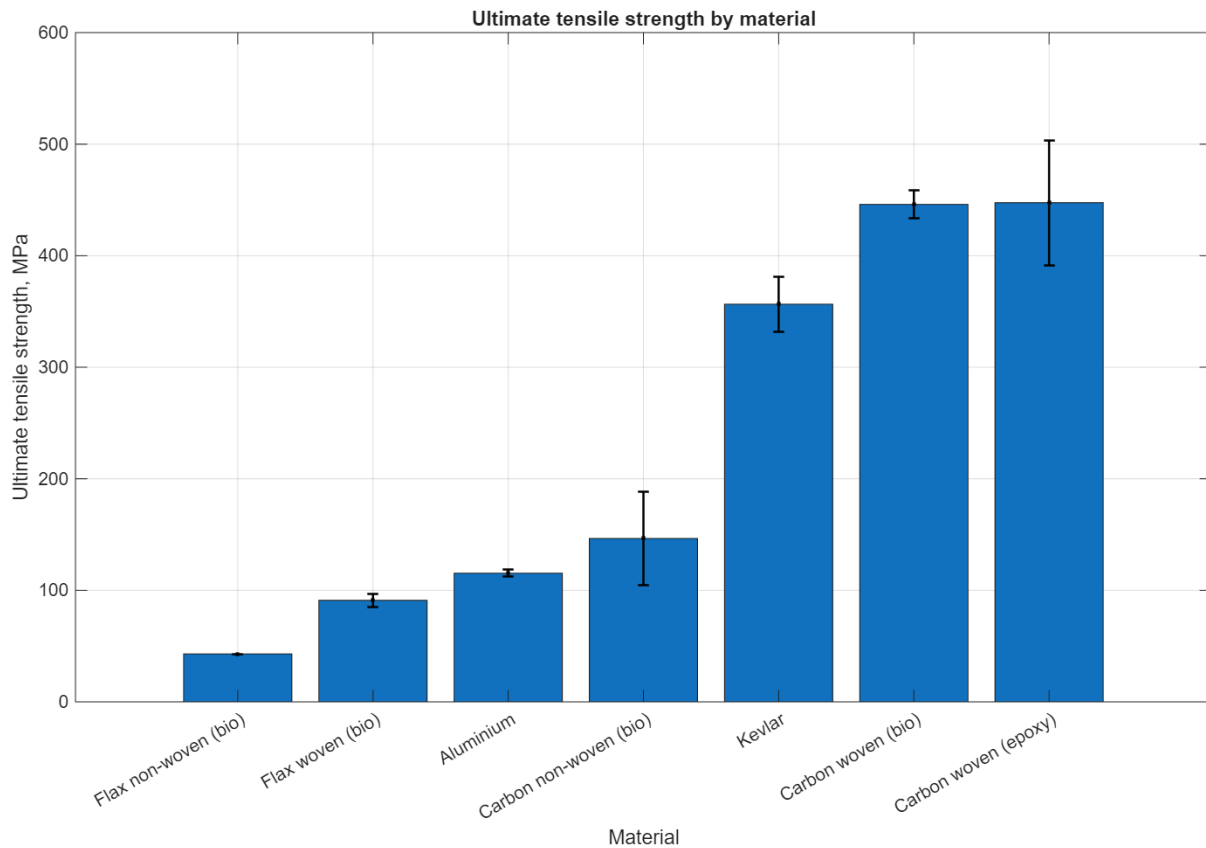


Figure 4 Mean ultimate tensile strength for each material

Figure 4 shows the mean ultimate tensile strength of the tested materials. The woven carbon composites produced the highest values overall, with carbon woven epoxy and carbon woven bio both giving mean strengths of approximately 445 MPa. Kevlar showed the next highest tensile strength at around 356 MPa, although this remained notably below the woven carbon systems. Carbon non-woven bio performed considerably less effectively, with a mean value of approximately 147 MPa and greater scatter between specimens. Aluminium produced a mean ultimate tensile strength of approximately 115 MPa, placing it above both flax-based composites but well below Kevlar and the woven carbon laminates. This shows that aluminium provided substantially lower tensile performance than the synthetic fibre composites.

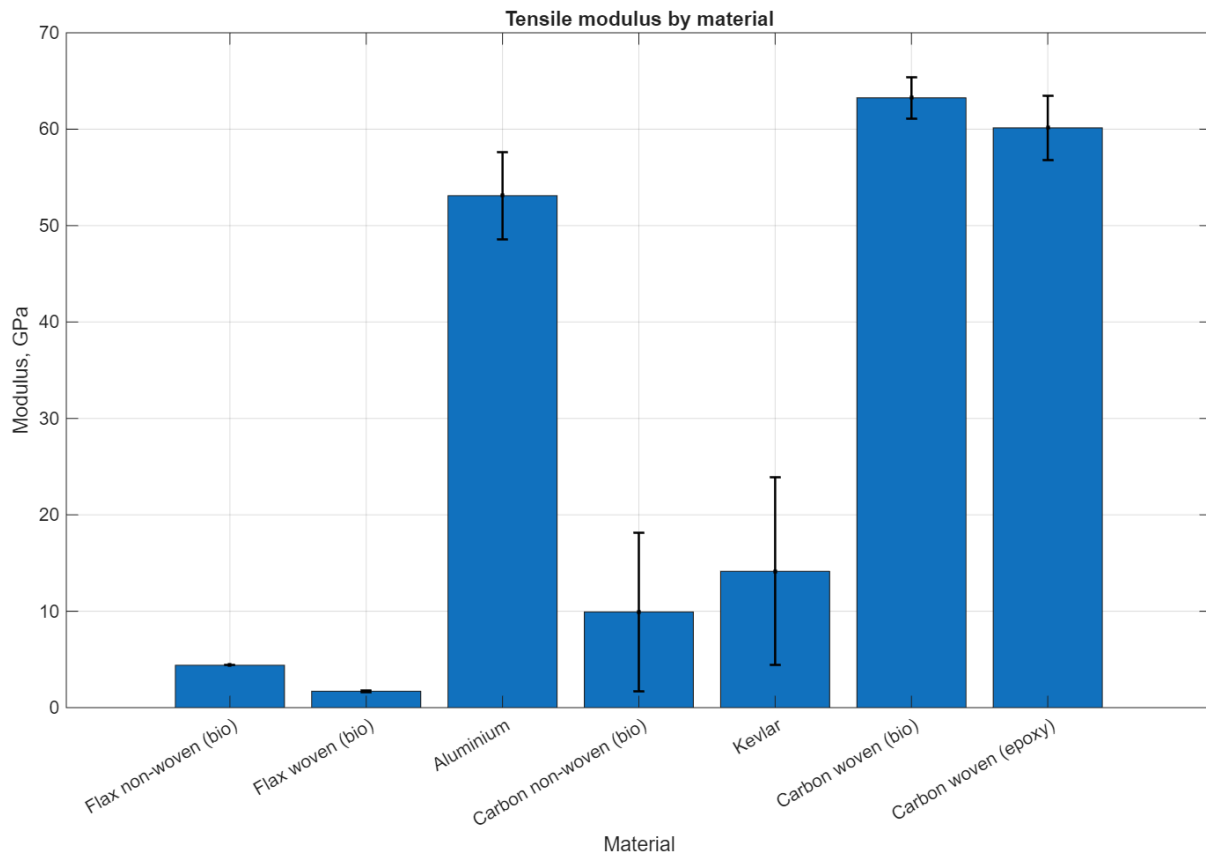


Figure 5 shows the Tensile Modulus by Material and its range in results from each test

Figure 5 shows the mean tensile modulus of the tested materials. The woven carbon composites exhibited the highest stiffness overall, with carbon woven bio giving the highest mean modulus at approximately 63 GPa and carbon woven epoxy following closely at around 60 GPa. Aluminium also demonstrated a relatively high modulus of approximately 53 GPa, indicating that while it did not match the tensile strength of the woven carbon systems, it remained significantly stiffer than Kevlar and the bio-based non-woven materials. Kevlar showed a much lower mean modulus of approximately 14 GPa and displayed a wide variation between specimens. Carbon non-woven bio produced a mean modulus of approximately 10 GPa, again with substantial scatter, while the flax-based materials recorded the lowest stiffness values overall. These results indicate that fibre architecture and reinforcement type had a strong influence on stiffness, with woven carbon laminates providing the most efficient structural response in tension. The flax-based materials recorded the lowest stiffness values overall, which agrees with Margoto and Milani (2025), who reported a tensile modulus of approximately 8.7 GPa for a woven flax bio epoxy composite.

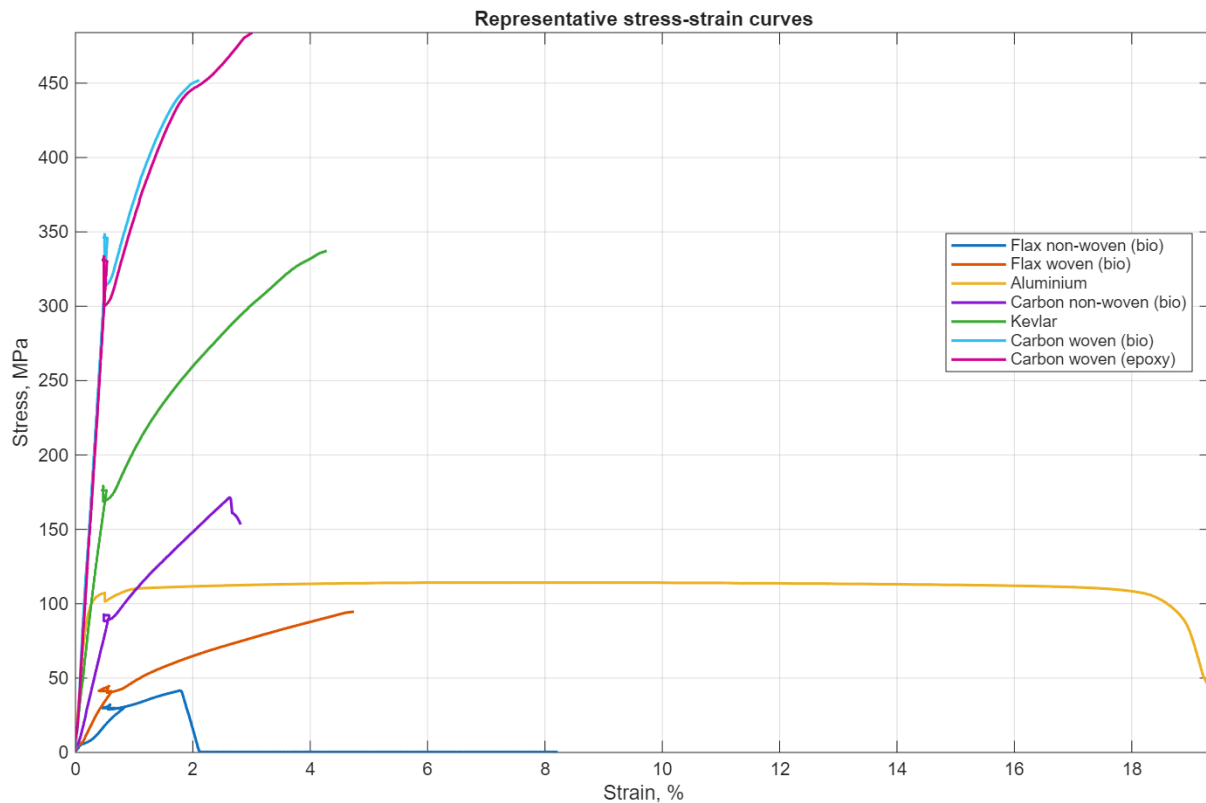


Figure 6 shows the stress strain curve for each test using the mean results of each material

Figure 6 shows the representative stress strain behaviour of the tested materials. The woven carbon composites displayed the steepest initial slope and the highest peak stresses, confirming that they provided the greatest combination of stiffness and tensile strength. Kevlar also achieved relatively high stress, but with a lower initial slope, indicating reduced stiffness compared with the woven carbon laminates. Carbon non-woven bio showed lower strength and stiffness than the woven carbon systems, suggesting that fibre lay-up had a strong influence on tensile response. The flax-based bio composites exhibited the lowest stresses throughout the test, confirming their reduced structural capability in tension. Aluminium differed from the composite systems by showing much greater strain to failure, reflecting its more ductile behaviour. Aligning with the findings of Simon McBeath (2009) with the woven fibre making a sharp increase using a resin matrix seeing tensile strength of 331 MPa at a 70 % glass content.

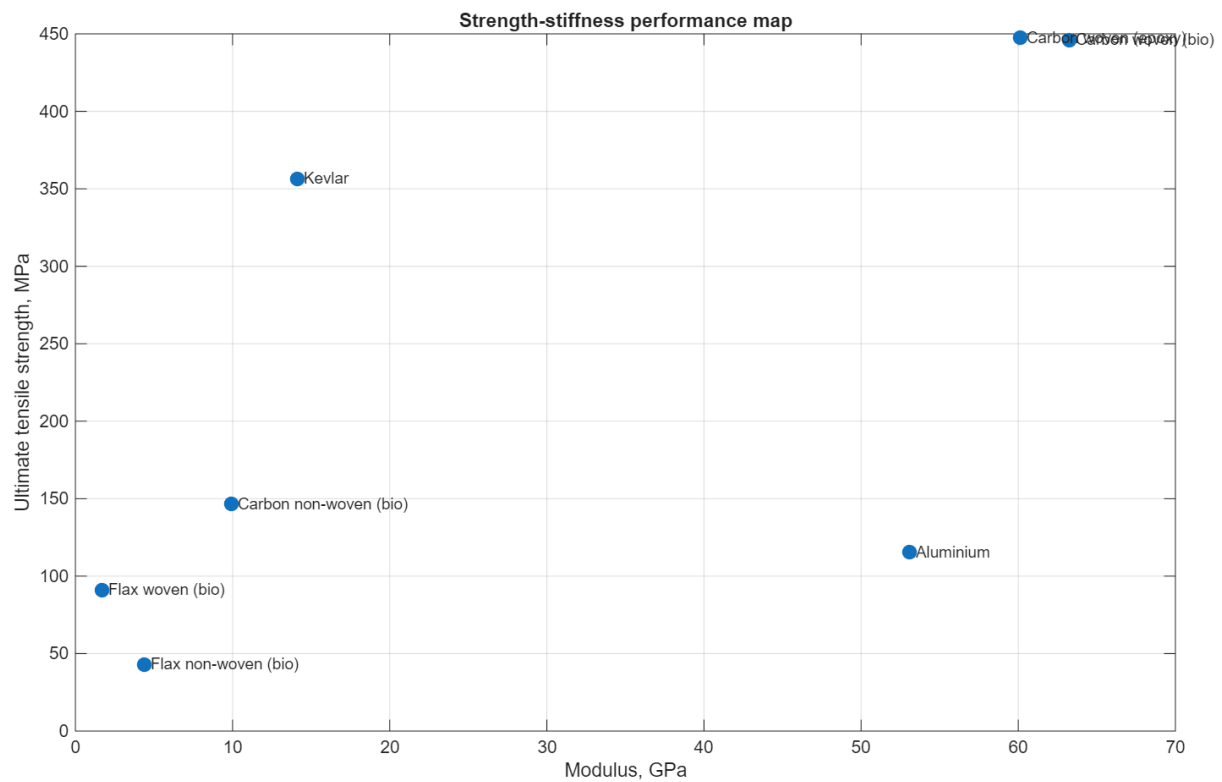


Figure 7 shows the strength- stiffness performance of each material

Figure 7 summarises the relationship between tensile strength and stiffness for the tested materials, showing that the woven carbon composites provided the best overall structural performance, while flax-based composites occupied the lowest-performance region.

6 Discussion

The tensile test results show a clear difference between the tested materials. The woven carbon composites gave the highest performance, with tensile strengths of around 445–487 MPa and modulus values of around 60–63 GPa. This is likely due to the high strength of carbon fibre and the woven structure, which allows load to transfer more effectively through the resin matrix. Compared with the carbon non-woven bio composite, which achieved around 147 MPa and 10 GPa, this shows that fibre architecture is just as important as fibre type. This agrees with McBeath (2009), who explains that aligned fibre structures are more effective at carrying load in composite laminates.

Kevlar also showed good tensile strength, reaching around 339–374 MPa, but its stiffness was much lower at approximately 14 GPa. This means it may be more suitable for impact-resistant or energy-absorbing components rather than stiffness-critical structures. Aluminium had a lower tensile strength of around 115 MPa but a relatively high modulus of around 53 GPa and greater strain before failure. This makes it useful where ductility, predictable failure and recyclability are important.

From a sustainability perspective, the results show a clear trade-off between performance and environmental impact. Carbon fibre offers the best strength and stiffness, but virgin carbon fibre production can require approximately 183–286 MJ/kg (Das, 2011; Yuan et al., 2024). Aluminium also has high primary production energy, typically around 170–220 MJ/kg, but recycled aluminium can reduce this by up to 90–95%, giving it a major circularity advantage (Khan et al., 2025).

The flax-based bio-composites had the lowest mechanical performance, with strengths of around 43–95 MPa and modulus values of approximately 2–5 GPa. However, they offer sustainability benefits due to their natural fibre content. Margoto and Milani (2025) reported a carbon footprint of around 2.93–3.32 kg CO₂/kg for flax-based bio-composites. Even so, their lower strength may require more material or more frequent replacement, so their environmental benefit must be considered across the full lifecycle.

This means material selection should not be based on strength, stiffness or sustainability alone. Carbon fibre may be justified in motorsport and high-performance applications where weight saving is critical. However, for lower-demand parts such as trim, interior panels or lightly loaded bodywork, flax-based composites or recycled materials may offer a better balance.

Some materials also showed greater scatter between repeat tests, particularly Kevlar and carbon non-woven bio. This suggests that fibre distribution, resin content, lay-up quality or defects may have influenced the results. This is important because consistent material behaviour is often as valuable as high peak performance in real engineering applications.

Overall, no single material is best for every use. Woven carbon fibre is most suitable for high-performance structural parts, aluminium provides a strong balance of stiffness, ductility and recyclability, and flax-based composites are better suited to non-critical components where sustainability is more important than maximum strength.

7 Conclusion

This report assessed the performance and sustainability of a range of materials used in automotive and motorsport engineering. The tensile test results showed that the woven carbon composites produced the highest ultimate tensile strength and modulus, confirming them as the best-performing materials for highly loaded structural applications. Kevlar also performed well in tension but showed lower stiffness, while aluminium remained a useful benchmark due to its moderate strength, relatively high stiffness and established recyclability. The flax-based bio-composites showed the lowest mechanical performance, indicating that their use is more appropriate in lower-demand or non-critical applications.

In conclusion, the results demonstrate a clear trade-off between mechanical performance and sustainability. Woven carbon composites remain the most suitable choice for maximum structural performance, but bio-based alternatives may offer environmental advantages where lower tensile performance can be accepted. Material selection should therefore be based on the specific balance required between strength, stiffness, consistency and sustainability.

8 Further work

Future work should involve producing the samples in-house so that all parameters, including lay-up, fibre orientation and manufacturing conditions, can be controlled more consistently during specimen production. Testing a greater number of specimens for each material would improve the reliability of the results and provide a better indication of the range within which failure may occur. In addition, different lay-up directions and alternative resin or epoxy systems could be investigated to assess their effect on stiffness, material response and failure modes.

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