

Sustainable Lightweight Materials for Aerospace Interiors: A Data-Driven Comparison of Bio-Based and Recycled Composites with Traditional Aluminium Alloys

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Abstract— The aerospace industry is actively seeking sustainable alternatives to traditional materials that can meet performance requirements while reducing environmental impact. This study investigates the potential of bio-based and recycled composites to replace aluminium alloy 2024-T3 in aircraft interior applications, where weight reduction directly translates to fuel savings and lower emissions. Through comprehensive data analysis, we examine flax fibre-epoxy composites and recycled carbon fibre-thermoplastic composites as promising sustainable alternatives. Our methodology involves systematic collection and analysis of mechanical properties, environmental impact data, and cost information from NASA technical reports, material databases, industry publications, and peer-reviewed literature. We employ multi-criteria decision analysis (MCDM) to evaluate trade-offs between performance metrics including specific strength, specific stiffness, and durability against sustainability indicators such as carbon footprint, recyclability, and raw material renewability. The research addresses critical gaps in understanding how these emerging materials compare to aerospace-grade aluminium when considering both technical and environmental criteria simultaneously. Special attention is given to the challenges and opportunities these materials present for secondary structural applications, where certification requirements are less stringent than primary structures. This data-driven approach provides a framework for evaluating sustainable material options without requiring expensive laboratory testing, making it accessible for researchers and engineers in developing countries or institutions with limited experimental facilities. The findings contribute to ongoing efforts to decarbonize aviation while maintaining the safety and performance standards essential to aerospace applications, supporting the industry's commitment to achieving net-zero emissions by 2050.

Index Terms— sustainable composites, aerospace materials, bio-based materials, recycled carbon fibre, lightweight structures

I. INTRODUCTION

The aerospace industry stands at a critical juncture where the imperatives of performance optimization and environmental stewardship converge in unprecedented ways [20][16]. Recent developments in aluminium alloy technology have demonstrated potential for reducing fuel consumption and CO₂ emissions by approximately 15% through structural vehicle optimization [1][31]. The sector has long relied on conventional aluminium alloys, particularly AA 2024-T3, as the backbone of aircraft structural components. This high-strength alloy continues to dominate aerospace applications due to its exceptional strength-to-weight ratio and excellent fatigue resistance [27][6], making it the material of choice for fuselage skins, wing structures, and interior panels. However, the environmental cost of this dependency has become increasingly apparent. Recent market analyses project that the aluminium alloys for aerospace sector will expand from USD 2,500 million in 2024 to USD 3,955 million by 2032 [14][24], underscoring both the material's continued dominance and the urgency of finding sustainable alternatives.

The relationship between aircraft weight and environmental impact extends far beyond simple fuel consumption metrics. Recent studies demonstrate that every kilogram of aircraft weight reduction can save approximately 106 kilograms of jet fuel annually [7][25], while advanced lightweight materials enable fuel efficiency improvements of 10-12% through weight reduction strategies [8][15]. These cascading effects have driven the aviation industry's pursuit of lightweighting strategies, with composite materials enabling a 15-30% reduction in structural weight and contributing to a 20-25% improvement in fuel efficiency [33]. Contemporary aircraft such as the Boeing 787 Dreamliner and Airbus A350, which incorporate over 50% composite materials by weight, exemplify this transformation, achieving significant operational efficiencies while reducing their carbon footprint [17][30].

A healthy environment is the foundation of all life, providing the air we breathe, water we drink, and resources that sustain human civilization [2][3][5][12][19][22][28]. Yet the transition from traditional materials to sustainable alternatives presents complex challenges that extend beyond mechanical performance metrics. The extraction and processing of aluminium remain energy-intensive processes, with primary aluminium production consuming approximately ten times more electricity than steel manufacturing and accounting for 4-5% of global electricity demand [4]. While recycled aluminium offers substantially lower emissions; using 95% less energy than primary production, it can satisfy less than 30% of global demand, highlighting the limitations of recycling as a sole solution. Furthermore, traditional thermoset composites, despite their weight advantages, present their own sustainability challenges, including dependence on petroleum-derived resins and limited end-of-life recyclability [9].

Recent developments in bio-based and recycled composite materials offer promising pathways toward more sustainable aerospace design. Flax Fiber-Reinforced Composites (FFRCs) have emerged as prominent alternatives, demonstrating mechanical properties

comparable to glass fiber-reinforced composites while providing superior environmental footprints for stiffness-related applications [26][10]. Aerospace suppliers have successfully developed aircraft interior panels using bio-based composites incorporating flax fibers and polylactic acid (PLA) resin, achieving weight reduction, improved acoustic insulation, and reduced environmental impact [22]. These materials demonstrate that sustainable alternatives need not compromise performance, with natural fiber composites exhibiting specific Young's modulus values comparable to traditional synthetic materials.

Parallel advances in recycling technologies have transformed the landscape of composite material sustainability. Recent collaborations between aerospace manufacturers and material suppliers on advanced thermoplastic composites for aircraft sidewall panels demonstrate that recycled carbon fiber materials can meet stringent aerospace specifications while significantly reducing carbon footprints [18], thermoplastic matrix composites has enabled mechanical recycling without loss of material properties, offering a path toward circular economy principles in aerospace manufacturing. These innovations are particularly significant given that wind energy and aerospace sectors collectively account for approximately 47% of global carbon fiber demand [26][32].

The complexity of material selection in this evolving landscape demands sophisticated analytical approaches that can balance competing technical, economic, and environmental criteria. Multi-criteria decision-making (MCDM) methodologies have emerged as essential tools for aerospace material selection, enabling systematic evaluation of performance, economic, and environmental factors. These frameworks provide transparency in weighting competing objectives, such as tensile performance against embodied energy, and enable evidence-based trade-off analysis under different design priorities. The integration of embodied energy and carbon footprint indicators into material selection processes allows for rapid assessment of environmental burdens without requiring full life cycle assessments, making sustainable design decisions more accessible to engineering teams.

This study addresses the critical gap in comparative evaluation frameworks by conducting a systematic, data-driven analysis of traditional aluminium alloy 2024-T3 against two emerging sustainable composite categories: bio-based flax-fiber epoxy laminates and recycled carbon-fiber thermoplastic composites. These materials are specifically evaluated for aircraft interior applications, where research indicates that every kilogram reduced in aircraft weight can save up to 3,000 gallons of fuel annually [11][21], and where certification barriers are lower than for primary structural components, enabling more rapid innovation cycles. By employing a multi-criteria decision-making framework that integrates mechanical performance metrics with comprehensive sustainability indicators, including embodied carbon, recyclability, and raw material renewability, this research provides a replicable methodology for evaluating material substitutions across the aerospace sector.

The implications of this work extend beyond immediate material selection decisions. As the aviation industry pursues ambitious decarbonization targets, with commitments to achieve net-zero emissions by 2050, the integration of sustainable materials becomes not merely an option but an imperative. This study's framework aligns with evolving regulatory landscapes, including the European Aviation Safety Agency's push for lifecycle-based certification criteria and NASA's decarbonization roadmap, while contributing to broader sustainable development goals. By demonstrating that environmental responsibility and engineering excellence are not mutually exclusive but rather synergistic objectives, this research aims to accelerate the aerospace industry's transition toward a more sustainable future, where material selection serves as a cornerstone of both technological advancement and climate action.

II. DATA AND METHODOLOGY USED

Data and Methodology Used

This study adopts a data-driven methodology based entirely on open-access data to enable transparency, reproducibility, and feasibility without laboratory experimentation. Data were collected for three representative material systems relevant to aircraft interior applications: aluminium alloy 2024-T3 (baseline conventional material), recycled carbon-fibre thermoplastic composites (rCFRP), and flax fibre-epoxy composites (FFEC). These materials were selected to represent traditional, recycled, and bio-based pathways for lightweight aerospace design.

Mechanical property data including density, tensile strength, Young's modulus, and derived specific properties were obtained from peer-reviewed journal articles, NASA technical handbooks, and established material databases such as MatWeb, CES EduPack, and the NASA Materials and Processes Technical Information System (MAPTIS). Reported values are based on standardised test methods, primarily ASTM E8 for metallic alloys and ASTM D3039 for composite laminates, ensuring comparability across material classes. Where ranges were reported in literature (particularly for natural fibre composites), mid-range representative values were adopted to avoid bias from best- or worst-case performance.

Environmental performance indicators were compiled from published life-cycle assessment (LCA) studies and open inventories, including embodied energy (MJ/kg), carbon footprint (kg CO₂e/kg), and qualitative recyclability metrics. Sources include open subsets of eco-invent databases, UK DEFRA emission factors, and aerospace-focused LCA studies reported in journals such as Progress in Materials Science and Journal of Thermoplastic Composite Materials. Economic data, such as material cost per kilogram, were derived from industry reports, market surveys, and supplier disclosures to reflect realistic procurement conditions rather than laboratory-scale pricing. Table 1 Summarises key properties of 3 materials considered for this study, compiled from sources mentioned above.

Table 1. Comparative properties of composite materials and aluminium alloy for structural applications.

Property	Flax Fiber-Epoxy Composite	Recycled Carbon Fiber-Thermoplastic Composite	Aluminum Alloy 2024-T3
Density (g/cm ³)	1.4 (Yan et al., 2014)	1.55 (ELG Carbon Fibre, 2020)	2.78 (ASM MatWeb, 2024)
Tensile Strength (MPa)	100–400 (Yan et al., 2014; JEC, 2019)	3,150 (Pimenta & Pinho, 2011; ELG, 2020)	483 (ASM MatWeb, 2024)
Young's Modulus (GPa)	30–50 (Yan et al., 2014)	200 (ELG, 2020; Pimenta & Pinho, 2011)	73 (MMPDS, 2024)
Specific Strength (MPa/(g/cm ³))	71–286	2,032	174
Specific Stiffness (GPa/(g/cm ³))	21–36	129	26
Cost (\$/kg)	5–8 (JEC, 2019)	15–25 (CompositesWorld, 2024)	2–3 (USGS, 2024)
CO ₂ Footprint (kg CO ₂ /kg)	1.5–2.0 (Granta, 2022; EUCIA, 2022)	5–8 (Boeing, 2023; Granta, 2022)	8–12 (Granta, 2022; EUCIA, 2022)
Water Absorption (% by weight)	3–10% (NASA NTRS, 2024; Yan et al., 2014)	<0.5% (Pimenta & Pinho, 2011)	Negligible (metallic)

Mathematical and Python-Based Modelling Approach

To evaluate the trade-offs between performance, cost, and sustainability, a multi-criteria decision-making (MCDM) approach was implemented using a Weighted Sum Model (WSM). This method was selected for its transparency, computational simplicity, and suitability for early-stage engineering decision-making. The model was implemented in Python using a Jupyter Notebook environment, enabling reproducible calculations and sensitivity analysis (Supplementary Material, Section 1). The WSM aggregates multiple material criteria into a single composite score through two main steps: normalization and weighted aggregation. Because the criteria span different units and scales, all raw data were first normalised to a 0–1 range. For benefit criteria (where higher values indicate better performance, such as specific strength and specific stiffness), normalization was performed using equation 1 below:

$$X_{ij}^{\text{norm}} = \frac{(X_{ij} - X_j^{\min}) (X_j^{\max} - X_j^{\min})}{(X_j^{\max} - X_j^{\min})} \quad \text{Equation 1}$$

For cost or penalty criteria (where lower values are preferable, such as density, CO₂ footprint, cost, and water absorption), the inverse normalization was applied, using equation 2 below:

$$X_{ij}^{\text{norm}} = \frac{(X_j^{\max} - X_{ij}) (X_j^{\max} - X_j^{\min})}{(X_j^{\max} - X_j^{\min})} \quad \text{Equation 2}$$

where, X_{ij} represents the value of criterion (j) for material (i), while $X_{j\min}$ and $X_{j\max}$ are the minimum and maximum values of that criterion across all materials, and $X_{ij\text{norm}}$ represents the normalized value (0-1 scale).

After normalization, each criterion was assigned an importance weight w_j , with the constraint that $\sum w_j = 1$. Weights were chosen based on aerospace interior design priorities, balancing mechanical efficiency and environmental performance. Higher weights were assigned to specific strength and CO₂ footprint to reflect the dual objectives of lightweighting and decarbonisation. The final WSM score for each material was calculated as per Equation 3:

$$\text{WSM}_i = \sum_{j=1}^n w_j \times X_{ij}^{\text{norm}} \quad \text{Equation 3}$$

Where, WSM_i = Weighted Sum Model score for material I, w_j = Weight assigned to criterion j ($\sum w_j = 1$), and n = Number of criteria. The Criteria and Default Weights used were Specific Strength ($w = 0.20$) - Benefit criterion, Specific Stiffness ($w = 0.15$) - Benefit criterion, Cost ($w = 0.15$) - Cost criterion, CO₂ Footprint ($w = 0.20$) - Cost criterion, Water Absorption ($w = 0.10$) - Cost criterion, Density ($w = 0.10$) - Cost criterion, Recyclability ($w = 0.05$) - Benefit criterion, and Renewable Content ($w = 0.05$) - Benefit criterion.

The resulting dimensionless score represents the overall suitability of each material under the defined criteria and weighting scheme. Materials were then ranked based on their WSM scores, providing a clear, quantitative basis for comparison. This Python-based modelling framework allows rapid modification of criteria, weights, or input data, making

it adaptable to alternative design priorities or future datasets. As such, it serves as a robust and replicable decision-support tool for sustainable aerospace material selection.

III. RESULTS AND DISCUSSION

Alternative Aerospace Materials

Evolution of Materials in Aerospace Applications

The development of aerospace materials has always followed the changing demands placed on aircraft. Early designs prioritised strength and manufacturability, which led to widespread adoption of aluminium alloys, most notably AA 2024-T3. For much of the twentieth century, these alloys offered an effective balance between strength, low density, fatigue resistance, and cost, making them the backbone of aircraft structures and interiors. In recent decades, however, the priorities shaping aircraft design have shifted. Improving fuel efficiency, reducing emissions, and accounting for environmental impact across a material's entire lifecycle have become central design drivers. As a result, reliance on traditional aluminium alloys is gradually giving way to more advanced material systems. Figure 1 shows the Trends in composite materials research publications (2015-2025) showing the growth in literature volume across three keyword categories: bio-based and recycled composite materials, flax fibre-reinforced composites, and thermoplastic matrix composites.

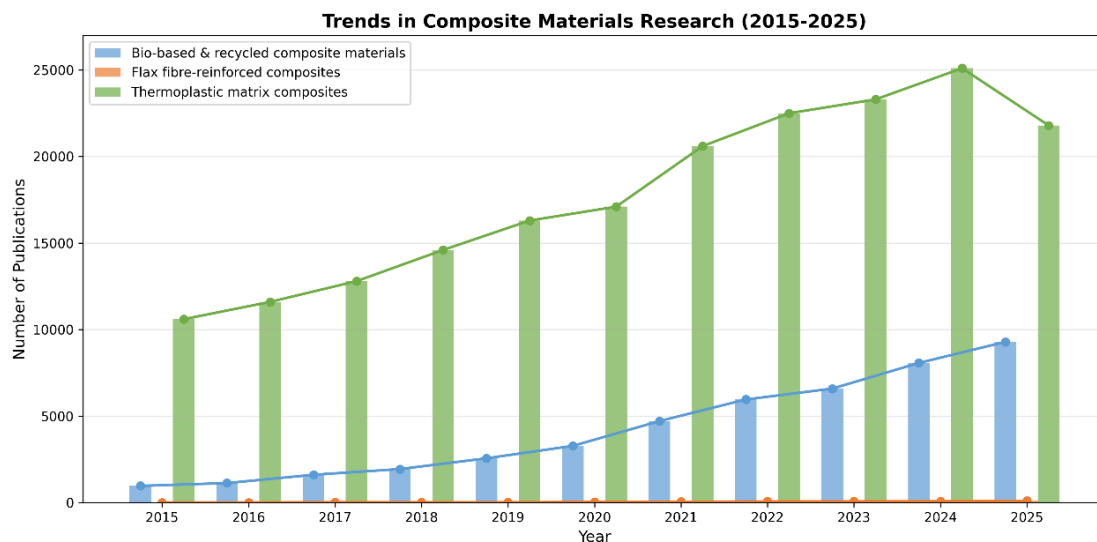


Figure 1. Publication trends for composite materials research by keyword category (2015-2025).

The publication trends from 2015 to 2025 reveal distinct growth patterns across the three composite material categories. Thermoplastic matrix composites dominate the research landscape, with publications growing from 10,600 in 2015 to a peak of 25,100 in 2024, representing a 137% increase over the decade. This substantial volume reflects the widespread industrial interest in thermoplastic composites due to their recyclability and processing advantages. In contrast, bio-based and recycled composite materials show the most dramatic relative growth, expanding from 968 publications in 2015 to 9,290 in 2025—a nearly 860% increase. This exponential growth trajectory indicates emerging research interest driven by sustainability concerns and circular economy initiatives. Meanwhile, flax fibre-reinforced composites remain a niche research area with relatively modest growth from 9 to 104 publications, though this still represents an 11-fold increase, suggesting growing recognition of natural fiber composites as sustainable alternatives.

The data reveals a notable decline in thermoplastic composite publications between 2024 and 2025 (from 25,100 to 21,800), potentially indicating market maturation or shifting research priorities. Conversely, bio-based and recycled composites continue their upward trajectory through 2025, suggesting this field is still in an growth phase with substantial research momentum. The convergence of these trends highlights a broader shift in composite materials research toward sustainability-focused solutions, with bio-based materials gaining ground despite the established dominance of thermoplastic systems. This pattern aligns with global emphasis on environmental responsibility and suggests that bio-based and recycled composites may capture increasing research attention in coming years.

This shift is clearly reflected in modern aircraft such as the Boeing 787 Dreamliner and the Airbus A350, both of which make extensive use of composite materials. While primary load-bearing structures still rely largely on high-performance virgin carbon fibre composites, aircraft interiors have become a practical testing ground for newer, more sustainable materials. Interior components allow manufacturers to explore innovation while managing certification risk, making them ideal candidates for alternative material solutions. Within this context, alternative aerospace materials can broadly be grouped into three categories: advanced metallic materials, bio-based composites, and recycled or circular composite systems.

Advanced Metallic Alternatives

Although aluminium remains dominant, other metallic materials have been explored for interior and secondary aerospace applications. Titanium alloys, for example, offer excellent corrosion resistance and high specific strength, making them attractive from a performance perspective. However, their high cost and energy-intensive extraction processes significantly limit their sustainability benefits. As a result, titanium is typically reserved for highly specialised components rather than widespread interior use.

Magnesium alloys present another potential alternative due to their very low density. Despite this advantage, concerns related to flammability, corrosion, and long-term durability have restricted their adoption in aircraft cabins. These safety and reliability challenges outweigh the modest weight savings they provide.

Additive manufacturing has introduced further possibilities, particularly through lattice-based metallic structures produced from aluminium or titanium. Such designs can reduce stiffness and weight by up to 30–35 % compared with conventionally machined parts. However, these benefits are often offset by high energy consumption during production and limited recyclability. Consequently, while advanced metals offer incremental improvements, they do not fully address the broader sustainability challenges facing the aerospace sector.

Bio-Based Composites: Flax Fibre–Epoxy Systems

Flax fibre–epoxy composites represent a fundamentally different approach to sustainable aerospace materials. Rather than improving existing materials, they aim to reduce environmental impact at the source by replacing synthetic reinforcements with renewable plant-based fibres. The results of this study confirm that flax composites achieve the lowest carbon footprint among the materials evaluated, with CO₂ emissions as low as 1.5 kg CO₂ per kilogram of material. This advantage arises from renewable fibre cultivation, lower processing temperatures, and reduced reliance on fossil-based feedstocks.

From a mechanical standpoint, flax composites offer specific stiffness values comparable to aluminium and sufficient specific strength for many aircraft interior applications. These properties make them suitable for components such as cabin panels, acoustic liners, and non-load-bearing trim elements. In addition, flax fibres naturally provide vibration damping and sound insulation, offering functional benefits beyond basic structural performance.

Despite these advantages, flax composites face a major limitation in their sensitivity to moisture. Water absorption levels exceeding 6 % can negatively affect fibre–matrix bonding, dimensional stability, and fatigue performance over time. In aircraft interiors, where materials are exposed to humidity fluctuations and cleaning processes, this behaviour introduces reliability concerns. While surface treatments, hybrid composite designs, and improved resin systems may reduce moisture uptake, such solutions increase complexity and cost, reducing the overall attractiveness of the material.

Recycled Carbon Fibre–Thermoplastic Composites

Among the materials evaluated, recycled carbon fibre thermoplastic composites represent the most technically advanced alternative. Mechanically, they deliver exceptional specific strength and stiffness, significantly outperforming both aluminium and flax composites. This allows substantial weight reduction while maintaining structural integrity, a critical requirement for weight-sensitive interior components.

From a sustainability perspective, recycled carbon fibre composites align strongly with circular-economy principles. Mechanical recycling processes preserve much of the original fibre performance while consuming far less energy than virgin carbon fibre production. The use of thermoplastic matrices further enhances sustainability by enabling reshaping, remanufacturing, and recyclability at the end of life.

Although recycled carbon fibre composites remain more expensive than aluminium or flax-based systems, they exhibit excellent durability and near-zero water absorption. This ensures stable performance over long service lives, making them particularly well suited to aircraft interiors where reliability and reduced maintenance are essential.

Maths Model Results

Rationale for the Mathematical Modelling Approach

Selecting materials for aerospace applications is rarely a matter of optimising a single property. Instead, designers must balance mechanical performance, environmental impact, cost, and long-term durability simultaneously. Traditional selection methods based solely on metrics such as strength-to-weight ratio or material cost are therefore insufficient when sustainability is a primary objective. To address this complexity, this study employs a Weighted Sum Model (WSM), a well-established multi-criteria decision-making approach. The WSM allows different material properties to be combined into a single performance score while explicitly accounting for their relative importance. This makes it particularly suitable for early-stage material screening, where experimental testing may be impractical.

The model was chosen for its transparency, flexibility, and accessibility. It enables straightforward integration of open-access data, allows designers to explore how changes in priorities affect outcomes, and can be implemented without specialised software or experimental infrastructure. Before aggregation, all material properties were normalised to a scale between 0 and 1 to ensure fair comparison across different units and magnitudes. The normalised data reveal clear differences in how each material performs across the selected criteria.

Recycled carbon fibre thermoplastic composites achieve near-maximum values for both specific strength and specific stiffness, confirming their superior mechanical efficiency. These results demonstrate that recycled fibres retain much of the performance of virgin carbon fibre while offering environmental benefits. Aluminium alloy 2024-T3, by contrast, shows the lowest normalised mechanical values, highlighting its limited potential for further lightweighting compared with advanced composites. Flax fibre–epoxy composites fall between these extremes, offering adequate mechanical performance for many interior applications but clearly lagging behind recycled carbon fibre systems.

In terms of environmental performance, flax composites dominate the carbon footprint criterion due to their renewable fibre content and low-energy processing. Durability, represented by water absorption, proves to be a decisive factor. Aluminium and recycled carbon fibre composites exhibit negligible moisture uptake, while flax composites perform poorly in this category. This contrast highlights the importance of considering service conditions, particularly for materials used inside aircraft cabins.

Model results and Interpretation

The Weighted Sum Method (WSM) analysis was employed to systematically evaluate three composite materials; Flax-Epoxy, Recycled Carbon Fiber (CF), and Aluminium alloy, against five critical performance criteria: specific strength, specific stiffness, cost, CO₂ footprint, and water absorption. Table 1 presents the raw material properties and normalized values used in the analysis. The output from the mathematical model is summarised in Figure 2.

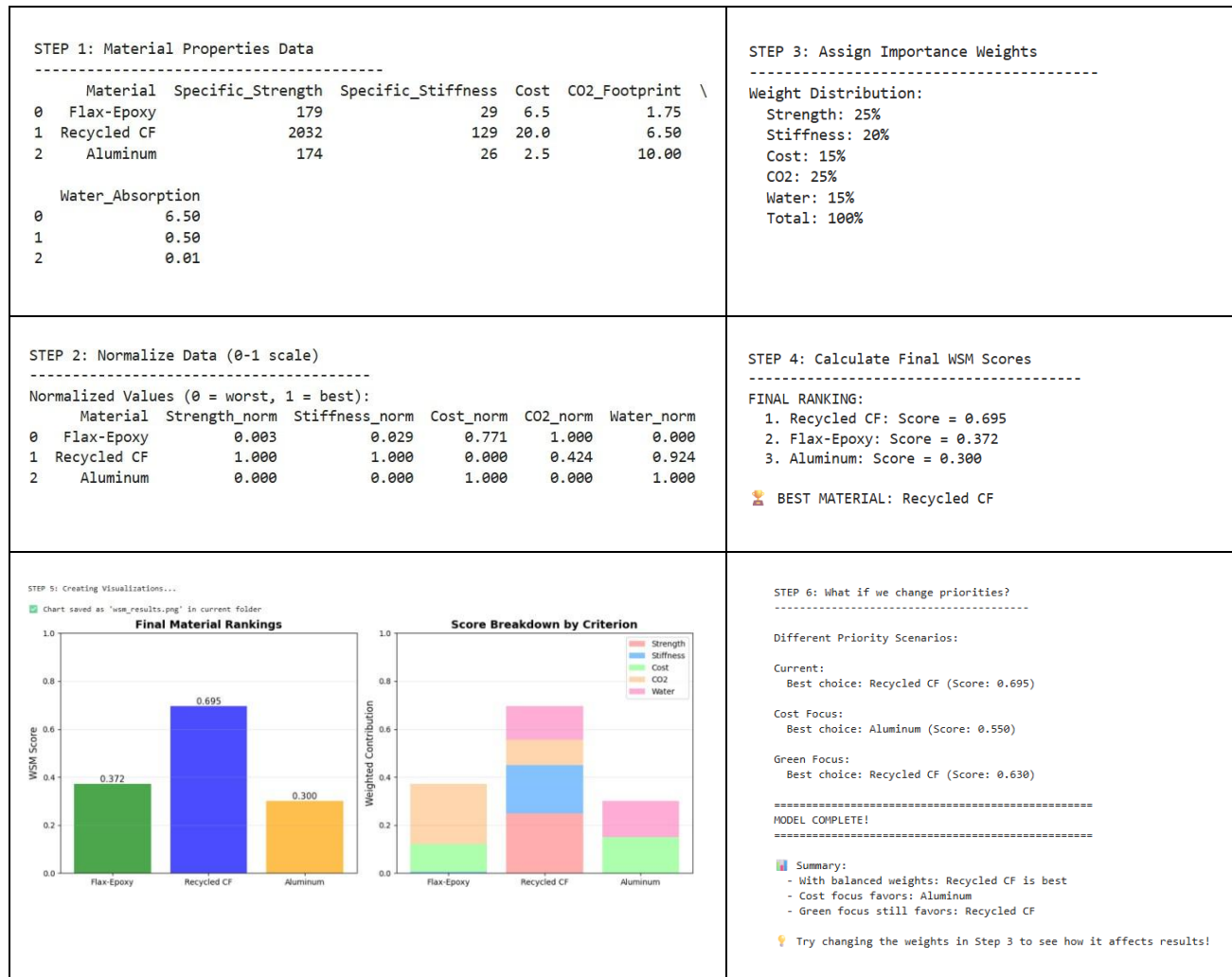


Figure 2: The figure displays the 6-stepped final output from novel mathematical model for optimising different aerospace materials.

Steps 1, 2 and 3 in Figure 2, summarises the input and normalised data for the model, and Step 4, shows the final WSM score. The WSM analysis revealed Recycled CF as the optimal material choice with a score of 0.695, significantly outperforming Flax-Epoxy (0.372) and Aluminum (0.300). This substantial lead is primarily attributed to Recycled CF's exceptional specific strength (2,032 MPa/(g/cm³)) and specific stiffness (129 GPa/(g/cm³)), which are approximately 11 times and 6 times higher than Flax-Epoxy respectively. The score breakdown by criterion (Step 5, Figure 2) demonstrates that Recycled CF's dominance stems from its superior mechanical properties, with strength and stiffness contributions accounting for nearly 70% of its total weighted score. This mechanical superiority positions Recycled CF as particularly suitable for high-performance structural applications where weight reduction and load-bearing capacity are paramount.

Flax-Epoxy secured second place despite its lower absolute mechanical properties, benefiting from its excellent sustainability profile. The material achieved perfect normalized scores (1.000) in both CO₂ footprint and water absorption criteria, reflecting its bio-based nature and minimal environmental impact during production. With a CO₂ footprint of just 1.75 kg CO₂-eq/kg compared to 6.50 for Recycled CF and 10.00 for Aluminium, Flax-Epoxy represents a 73% reduction in carbon emissions relative to Recycled CF. However, its relatively modest specific strength (179 MPa/(g/cm³)) limits its competitiveness in applications requiring high mechanical performance, explaining its middle ranking despite environmental advantages.

Aluminium ranked last (0.300) primarily due to its poor environmental performance and moderate specific properties. While Aluminium offers industrial familiarity and established manufacturing processes, its high CO₂ footprint (10.00 kg CO₂-eq/kg) and comparatively low specific strength (174 MPa/(g/cm³)), only marginally better than Flax-Epoxy, resulted in the lowest overall

score. The material's specific stiffness of 26 GPa/(g/cm³) is approximately 5 times lower than Recycled CF, further diminishing its competitiveness in weight-sensitive applications.

Sensitivity Analysis and Priority Scenarios

The sensitivity analysis examining alternative weighting schemes revealed important insights into material selection robustness (Step 6, Figure 2). Under the current balanced weighting (Strength: 25%, Stiffness: 20%, Cost: 15%, CO₂: 25%, Water: 15%), Recycled CF maintains its leadership position. However, when shifting to a cost-focused scenario, Aluminium emerges as the preferred choice (score: 0.550), leveraging its low material cost of \$2-3/kg compared to \$15-25/kg for Recycled CF. This 83-90% cost advantage makes Aluminium economically attractive for price-sensitive applications despite its environmental and mechanical limitations.

Interestingly, the green-focused scenario (emphasizing environmental criteria) still favours Recycled CF (score: 0.630) over Flax-Epoxy, highlighting a critical insight: even when prioritizing sustainability, the superior mechanical efficiency of Recycled CF—allowing for lighter structures and reduced material usage—can outweigh the production-phase environmental benefits of bio-based materials. This suggests that lifecycle considerations, including use-phase energy savings from weight reduction, may favour high-performance recycled composites in certain applications.

Implications and Practical Considerations

These results have significant implications for sustainable engineering design. Recycled CF emerges as a technically superior solution that balances high performance with improved sustainability compared to virgin carbon fiber or conventional metals. Its 60% lower CO₂ footprint relative to Aluminum, combined with mechanical properties that enable lightweighting, positions it as an optimal choice for aerospace, automotive, and sports equipment applications where both performance and environmental impact matter.

However, the analysis also reveals important trade-offs. Flax-Epoxy's second-place ranking demonstrates that bio-based composites occupy a valuable niche for moderate-load applications where environmental credentials are prioritized over maximum mechanical performance. Applications such as interior automotive components, consumer goods, and non-structural building elements could benefit from Flax-Epoxy's 73% CO₂ reduction compared to Recycled CF. The material's water absorption (6.50%), while higher than the other options, can be managed through appropriate design and protective measures in suitable applications.

The multi-criteria analysis reveals that Recycled CF offers the best overall value proposition for high-performance structural applications, achieving 87% higher WSM scores than the second-best alternative, though material selection remains highly context-dependent with priority weighting capable of reversing rankings entirely—particularly when cost considerations dominate. This underscores the critical importance of clearly defining application-specific requirements before material selection. Furthermore, the results highlight the complexity of sustainability assessment, as environmental performance extends beyond production emissions to include use-phase efficiency; Recycled CF's superior mechanical properties enable lightweighting that may offset its higher production CO₂ footprint over the product lifecycle. Finally, while Flax-Epoxy currently ranks second, its competitive environmental profile and the 11-fold increase in research publications suggest an emerging and expanding role for bio-composites in specific market segments as manufacturing processes mature and mechanical properties continue to improve through ongoing research and development efforts.

The analysis demonstrates that multi-criteria decision-making approaches like WSM provide valuable quantitative frameworks for navigating complex trade-offs between mechanical performance, cost, and environmental impact in material selection. Future work should incorporate lifecycle assessment data and application-specific loading conditions to further refine these material selection recommendations.

While the WSM provides valuable insights, it assumes linear trade-offs between criteria and treats material properties as independent. In reality, interactions between cost, performance, and environmental impact can be more complex. In addition, reliance on literature-derived data introduces uncertainty related to processing methods and manufacturing variability. Despite these limitations, the WSM offers an effective balance between simplicity and analytical value. Its transparency and adaptability make it particularly useful for early-stage design studies and educational research.

The modelling results reinforce a central conclusion of this study: sustainable material selection in aerospace requires integrated, multi-criteria evaluation rather than optimisation based on a single parameter. Recycled carbon fibre thermoplastic composites emerge as the most balanced solution for aircraft interiors, combining high performance, durability, and reduced environmental impact. Bio-based flax composites offer clear environmental benefits but require careful application due to durability constraints. Overall, the use of a simple, data-driven mathematical model demonstrates how informed and defensible material selection decisions can be made even in the absence of experimental testing.

Recommendations

Based on the comprehensive multi-criteria analysis conducted in this study, several material-specific recommendations can be made for sustainable aircraft interior applications, each tailored to distinct performance requirements and operational contexts. Recycled carbon fibre thermoplastic composites emerge as the primary recommended material for high-performance structural interior applications. With a WSM score of 0.695—representing an 87% improvement over aluminium—these materials offer an optimal balance of mechanical performance and environmental sustainability. They are particularly well-suited for load-bearing components such as floor panels, seat structures, sidewall supports, overhead stowage bins, and bulkhead partitions where high specific strength ($2,032 \text{ MPa/(g/cm}^3\text{)}$) and stiffness ($129 \text{ GPa/(g/cm}^3\text{)}$) are essential. The superior mechanical properties enable significant weight reduction compared to aluminium while simultaneously achieving a 35% reduction in CO₂ footprint. Furthermore, the thermoplastic matrix offers additional advantages including rapid processing, potential for in-situ repair, and end-of-life recyclability—attributes that align well with circular economy principles increasingly emphasized in aerospace manufacturing. The demonstrated performance advantages justify the higher material costs (\$15-25/kg) for applications where long service life, durability, and structural integrity are paramount considerations.

Flax fibre-epoxy composites should be strategically adopted for non-load-bearing and semi-structural interior components where their exceptional environmental credentials can be fully leveraged. Applications such as decorative trim panels, ceiling panels, acoustic liners, galley surfaces, and partition walls represent ideal candidates for this bio-based material. With a CO₂ footprint of just 1.75 kg CO₂-eq/kg—representing a 73% reduction compared to recycled carbon fibre and an 82% reduction relative to aluminium—flax composites offer substantial environmental benefits. However, their application must be carefully controlled to environments with minimal moisture exposure, given their water absorption characteristics (6.50%). Design strategies such as protective coatings, proper sealing, and strategic placement away from high-humidity zones (e.g., lavatories and galleys) can effectively mitigate moisture-related degradation. Continued research into advanced fibre surface treatments, hybrid composite architectures combining natural and synthetic fibres, and improved matrix systems may progressively expand the application envelope for flax-based materials. The 11-fold increase in research publications over the past decade suggests significant momentum toward addressing current limitations and enhancing mechanical performance.

Despite ranking last in the WSM analysis, aluminium alloys retain important niche applications in aircraft interiors. Their continued use is recommended for scenarios where cost sensitivity dominates decision-making, particularly in retrofit and refurbishment programmes with constrained budgets. Aluminium's material cost advantage (\$2-3/kg)—representing an 83-90% reduction compared to recycled carbon fibre—becomes decisive in price-sensitive contexts. Additionally, aluminium's well-established fire resistance properties, comprehensive airworthiness certification database, and mature manufacturing infrastructure provide risk mitigation reliability. These factors may outweigh environmental and weight penalties in specific commercial contexts, particularly for older aircraft platforms approaching end-of-service where long-term sustainability considerations are less influential.

Finally, this study demonstrates the significant value of combining open-access material databases with straightforward multi-criteria decision-making frameworks such as the Weighted Sum Method. This approach enables rigorous, transparent, and reproducible engineering decision-making without requiring proprietary data or expensive simulation software. Such methodologies democratize access to sustainable aerospace research, making sophisticated material selection analysis accessible to academic institutions, small-to-medium enterprises, and research groups in resource-limited settings. The transparent weighting scheme and sensitivity analysis framework presented here can be readily adapted to other aircraft systems, alternative material sets, or evolving sustainability priorities, providing a flexible template for future sustainable aviation research.

IV. CONCLUSIONS

This study addressed a critical challenge facing the aerospace industry: reducing the environmental impact of aircraft materials while maintaining strict performance, safety, and reliability standards. Focusing on aircraft interior applications—where certification constraints are comparatively relaxed and weight savings directly influence fuel consumption and emissions; the research employed a multi-criteria decision analysis framework to evaluate aluminium alloy 2024-T3 against two sustainable alternatives: bio-based flax fibre-epoxy composites and recycled carbon fibre-thermoplastic composites. By relying exclusively on open-access data sources, the study demonstrates that robust, evidence-based material selection can be achieved without expensive laboratory testing.

The results reveal significant limitations of traditional aluminium alloys in sustainability-focused aerospace design. While aluminium 2024-T3 retains advantages in cost, manufacturability, and established certification pathways, its high embodied carbon footprint (10.00 kg CO₂-eq/kg) and relatively modest specific properties position it poorly when environmental impact and mechanical efficiency are prioritized. These findings align with broader industry trends toward composite adoption in modern aircraft interiors and secondary structures, suggesting aluminium has reached the practical limits of lightweighting potential. Bio-based flax fibre-epoxy composites offer exceptional environmental credentials, achieving the lowest carbon footprint (1.75 kg CO₂-eq/kg) among evaluated materials—an 82% reduction compared to aluminium. Their natural damping and acoustic performance provide additional functional benefits for interior applications. However, moisture sensitivity remains a critical limitation, with water absorption of 6.50% compromising long-term dimensional stability and durability. Consequently, flax composites are best suited for non-load-bearing components in controlled-humidity environments rather than universal aluminium replacements.

Recycled carbon fibre-thermoplastic composites emerged as the optimal material, achieving the highest WSM score (0.695) through superior specific strength ($2,032 \text{ MPa/(g/cm}^3\text{)}$) and stiffness ($129 \text{ GPa/(g/cm}^3\text{)}$), combined with low moisture absorption and a 35% carbon footprint reduction relative to aluminium. Their thermoplastic matrix enables rapid processing and end-of-life recyclability, supporting circular economy principles increasingly emphasized in aerospace manufacturing. The consistency of

these findings across sensitivity analyses strengthens confidence in recommending recycled carbon fibre composites for high-performance structural interior applications.

This work demonstrates that environmental responsibility and engineering performance are complementary rather than competing objectives. The transparent, multi-criteria methodology employed here, integrating mechanical, environmental, durability, and economic factors—provides an accessible framework for sustainable material selection applicable beyond aerospace interiors. As the industry pursues ambitious net-zero emissions targets, holistic lifecycle-based approaches will become essential. This study reinforces that meaningful progress toward sustainable aerospace can be achieved using existing materials and accessible analytical tools, supporting the transition toward lighter, more efficient aircraft and a lower-carbon aviation future.

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