American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)

E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Lightweight Composite Innovation for Sustainable Mobility Applications

Dr. Thomas Becker

Professor, RWTH Aachen University, Germany

Abstract

Lightweight composite materials are increasingly important in the transition toward sustainable mobility because vehicle mass directly influences energy demand, structural efficiency, payload capability, driving range, and the amount of material required to deliver mobility functions. The environmental value of lightweighting, however, cannot be determined from mass reduction alone. High-performance composites may reduce operational energy consumption while simultaneously increasing environmental burdens during raw-material production, manufacturing, repair, or end-of-life treatment. This study develops an integrated framework for evaluating lightweight composite innovation across automotive and electric-mobility applications.

Because no experimental materials dataset or vehicle-level field data were supplied, the quantitative component is explicitly structured as a simulation-based methodological study. Four hypothetical material strategies are evaluated: conventional metal-dominant construction, glass-fiber-reinforced polymer hybrid lightweighting, recycled or bio-based composite construction, and an integrated circular hybrid composite system. Five performance dimensions are considered: mass efficiency, structural performance, manufacturing feasibility, life-cycle sustainability, and circularity. The simulated Composite Sustainable Mobility Score increases from 55 for the conventional material architecture to 70 for the glass-fiber hybrid, 82 for the recycled or bio-composite strategy, and 91 for the integrated circular hybrid system.

The analysis suggests that the strongest mobility solution does not emerge from maximizing weight reduction independently. Instead, sustainable lightweighting requires simultaneous optimization of specific mechanical performance, manufacturability, durability, cost, material origin, repairability, recycling, and vehicle-level energy benefits. The study proposes a Sustainable Lightweight Composite Decision Framework suitable for future validation through mechanical testing, finite-element analysis, vehicle-energy simulation, life-cycle assessment, cost analysis, and recycling experiments. The findings emphasize the transition from lightweight materials toward lightweight circular material systems.

Keywords: lightweight composites; sustainable mobility; electric vehicles; automotive composites; natural-fiber composites; recycled carbon fiber; thermoplastic composites; life-cycle assessment; circular materials; vehicle lightweighting

1. Introduction

Transportation systems are undergoing simultaneous transitions in propulsion technology, material engineering, digitalization, manufacturing, and environmental performance. Battery-electric vehicles, hybrid vehicles, lightweight public transport, micromobility systems, advanced rail platforms, and future low-emission mobility architectures all place new demands on structural materials. Vehicle designers increasingly require materials that provide low density, sufficient stiffness, high strength, durability, crash performance, manufacturability, and economically realistic production.

Lightweighting is one of the most established strategies for improving the efficiency of mobility systems. Reducing structural mass can lower the energy required for acceleration and movement while potentially improving vehicle range, payload utilization, braking response, and component downsizing opportunities. Advanced automotive material reviews consequently identify high-strength steels, aluminum, magnesium, fiber-reinforced polymers, and hybrid materials as major candidates for next-generation lightweight vehicle structures.

The importance of mass reduction is especially visible in electric mobility. Electric vehicles incorporate battery packs that contribute substantial mass to the overall vehicle architecture. Composite materials can therefore support lightweight body structures, battery enclosures, interior components, suspension elements, panels, energy-absorbing structures, and other mobility components where high specific mechanical performance is required. Reviews of composite applications in electric vehicles identify carbon-fiber-reinforced polymers, glass-fiber composites, thermoplastic composites, and hybrid structures as significant candidate material systems.

A lighter component may consume less operational energy but require considerably more energy during raw-material production. Carbon fiber, for example, can deliver exceptional strength- and stiffness-to-weight performance, but conventional carbon-fiber production and several composite manufacturing processes can create significant environmental burdens. Comparative life-cycle research has therefore demonstrated that the environmental advantage of carbon-fiber composites depends strongly on material formulation, manufacturing method, operating benefit, functional life, and end-of-life pathway.

Natural fibers, recycled carbon fibers, bio-based matrices, thermoplastic composites, hybrid fiber systems, recyclable resins, and material-efficient manufacturing processes are therefore receiving growing research attention. Recent mobility-focused literature identifies natural-fiber-reinforced polymer composites as promising for automotive lightweighting, particularly where moderate structural requirements allow renewable low-density reinforcement to replace more energy-intensive alternatives. The present study investigates this broader sustainability challenge through an integrated material-selection perspective.

2. Lightweighting in Sustainable Mobility

Vehicle mass influences several aspects of transportation performance. Lower mass can reduce the energy required during acceleration, decrease structural loads on other components, and create opportunities for secondary mass reductions when brakes, suspension, powertrain components, or batteries can be resized.

The exact energy benefit depends on vehicle type, propulsion technology, driving cycle, aerodynamics, regenerative braking, route profile, and component location. Consequently, a fixed relationship between Regenerative braking can recover part of the kinetic energy associated with vehicle mass, reducing some of the use-phase advantage of lightweighting.

At the same time, reducing EV mass can increase range, improve performance, reduce tire and brake loads, and potentially permit battery downsizing in optimized vehicle architectures. Research on EV composites therefore emphasizes that lightweight solutions should be evaluated at complete vehicle-system level rather than through direct material substitution alone.

3. Composite Materials for Mobility Applications

3.1 Carbon-Fiber-Reinforced Polymer Composites

Carbon-fiber-reinforced polymer composites provide very high specific stiffness and specific strength. These properties make CFRP attractive for structural panels, monocoques, reinforcement members, battery structures, performance vehicles, aerospace mobility, and other weight-sensitive applications.

Conventional carbon-fiber production can be energy intensive, while thermoset matrices create additional end-of-life difficulties because cured components cannot simply be remelted in the same manner as thermoplastic materials.

Life-cycle analysis is therefore essential when CFRP is compared with aluminum or steel. Atescan-Yuksek and colleagues' comparative analysis of aluminum and different CFRP systems showed that composite environmental performance varies significantly according to manufacturing route and constituent materials rather than being determined solely by mass reduction.

3.2 Glass-Fiber-Reinforced Polymer Composites

Glass-fiber-reinforced polymers provide lower material cost than many carbon-fiber systems while maintaining useful specific strength, corrosion resistance, and manufacturing flexibility.

They are widely relevant to semi-structural automotive parts, exterior panels, battery-system components, transportation interiors, leaf springs, covers, and other applications.

The density of glass fiber is higher than carbon fiber or many natural fibers, and its stiffness-to-weight performance is lower than CFRP. Nevertheless, GFRP can provide an economically realistic compromise between metallic construction and premium carbon-fiber composites.

4. Natural-Fiber and Bio-Based Composites

Natural fibers such as flax, hemp, jute, kenaf, sisal, and other plant-derived reinforcements offer low density and renewable material origin.

They are particularly attractive for interior panels, door components, seat structures, trim systems, parcel shelves, acoustic panels, and selected semi-structural applications.

Recent reviews identify natural-fiber-reinforced polymer composites as increasingly relevant to eco-friendly automotive lightweighting, while also emphasizing continuing challenges involving moisture sensitivity, fiber variability, interface quality, thermal stability, durability, fire behavior, and structural qualification.

A recent life-cycle study of natural-fiber/polypropylene composite side skirts for electric trucks reported substantially lower climate impact for the studied composite solution than the incumbent plastic-and-steel configuration, illustrating the potential of carefully selected natural-fiber thermoplastic systems in commercial mobility applications.

5. Thermoplastic Composites and Circularity

Thermoplastic composites have become important to sustainable lightweighting because thermoplastic matrices can be softened and reshaped through heating.

This characteristic creates opportunities for faster production cycles, welding, remanufacturing, mechanical recycling, reuse of production scrap, and recovery of material value.

Recycling is not automatic, however.

Fiber length degradation, contamination, matrix degradation, mixed-material assemblies, adhesives, coatings, and component geometry can reduce the quality of recovered material.

Türker, Özturk, and Öz reviewed thermoplastic composite recycling methods and identified mechanical, thermal, and chemical routes as important approaches, each with different energy demands and recovered-material characteristics.

6. Recycled Carbon Fiber

Recycled carbon fiber represents another pathway toward more sustainable high-performance composites.

Manufacturing scrap and end-of-life carbon-fiber components contain valuable reinforcement that can potentially be recovered through mechanical, thermal, or chemical processes.

Recovered fibers may not retain the same architecture or performance as continuous virgin fibers, but they can be valuable in short-fiber thermoplastic compounds, sheet-molding systems, nonwoven structures, additive manufacturing feedstock, and semi-structural components.

Barnett and colleagues demonstrated a zero-waste-oriented manufacturing approach for carbon-fiber-reinforced thermoplastic composites, illustrating the potential for integrating production scrap directly into circular manufacturing systems.

7. Hybrid Composite Architectures

Hybrid composites combine two or more reinforcement or material families within a single component or vehicle structure.

Examples include carbon/glass-fiber hybrids, natural/synthetic fiber combinations, fiber-metal laminates, thermoplastic composite–metal assemblies, and components containing both virgin and recycled reinforcement.

Instead of using expensive high-performance carbon fiber throughout an entire component, it can be concentrated in critical load paths while glass fiber, recycled fiber, natural fiber, or lightweight metal carries less demanding loads.

American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)
E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

8. Manufacturing Innovation

Material sustainability is strongly influenced by manufacturing technology.

Autoclave processing can produce high-quality composites but is generally expensive and energy intensive.

Alternative methods include resin-transfer molding, compression molding, injection molding, thermoforming, automated fiber placement, pultrusion, filament winding, and increasingly automated thermoplastic processing.

Mass-market mobility requires manufacturing technologies with short cycle time, stable quality, low scrap rates, and compatibility with high production volumes.

9. Safety and Structural Performance

Sustainable mobility materials cannot compromise safety.

Composite structures must meet application-specific requirements for static strength, stiffness, fatigue, impact resistance, crash energy management, thermal stability, environmental aging, and fire behavior.

Battery-electric vehicles create additional requirements because materials used near battery systems may need electrical insulation, flame resistance, thermal protection, and controlled failure behavior.

Mohanty and colleagues emphasized the simultaneous importance of lightweighting and flame-retardant performance in sustainable EV composite development, particularly in the context of battery-related thermal hazards.

10. Life-Cycle Sustainability

Life-cycle assessment provides one of the most important methods for evaluating lightweight materials.

A complete mobility-material comparison should include raw-material extraction, reinforcement production, polymer or metal production, manufacturing, transportation, vehicle use, maintenance, replacement, and end-of-life treatment.

Gonçalves, Monteiro, and Iten's overview of automotive lightweight LCA studies emphasizes that environmental conclusions vary according to system boundaries, vehicle technology, material assumptions, energy mix, lifetime, and recycling scenarios.

This variability is crucial.

A high-production-impact lightweight composite may be environmentally favorable in a long-lived, highly utilized vehicle but unfavorable in another application.

11. Research Gap

The existing literature identifies several unresolved challenges.

First, lightweighting research frequently optimizes mechanical properties before conducting environmental assessment. This can result in technically excellent materials that are difficult to justify on a life-cycle basis.

Second, recycled and bio-based composites are often compared with virgin materials through generalized sustainability claims without sufficient consideration of mechanical equivalence.

American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)
E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Third, many studies evaluate materials individually rather than examining hybrid architectures capable of placing premium reinforcement only where structurally necessary.
Fourth, manufacturing, repair, and end-of-life performance remain insufficiently integrated within early-stage material selection.

12. Novelty and Proposed Contribution

The study proposes the Sustainable Lightweight Composite Decision Framework (SLCDF).
The framework treats lightweight composite innovation as the simultaneous optimization of five dimensions:

- Mass Efficiency
- The material should achieve required structural function using minimal vehicle mass.
- Structural Performance
- Mechanical, fatigue, impact, thermal, durability, and safety requirements must be maintained.
- Manufacturing Feasibility
- The material should be compatible with realistic cycle times, quality control, automation, cost, and production scale.
- Life-Cycle Sustainability

Environmental burdens from raw materials, manufacturing, vehicle use, maintenance, and end-of-life management must be evaluated together.

13. Research Objectives

The study has five objectives:

1. To examine the sustainability potential of lightweight composite materials in mobility applications.
2. To compare conventional metallic, glass-fiber hybrid, bio/recycled composite, and circular hybrid strategies.
3. To evaluate the relationship between structural lightweighting and life-cycle environmental performance.
4. To identify major barriers to the large-scale adoption of sustainable composites.
5. To develop a decision framework for future sustainable mobility-material selection.

14. Research Questions

- Does increasing composite content necessarily improve the sustainability of a mobility structure?
- How do natural-fiber and recycled composites compare conceptually with conventional lightweight materials?
- Can hybrid material architectures provide a stronger balance between mechanical performance and environmental sustainability?
- How do manufacturing and end-of-life conditions affect the sustainability of lightweight composites?
- Which performance dimensions should mobility designers evaluate before selecting a sustainable composite system?

15. Methodology

15.1 Research Design

1. The study employs a simulation-based multi-criteria comparative design.
2. No physical tensile, flexural, fatigue, impact, fire, or crash tests were conducted.
3. No real vehicle energy-consumption dataset was used.
4. The numerical scores are synthetic and are intended to demonstrate how alternative material strategies could be evaluated in a future experimental study.
5. Four hypothetical material architectures were considered.

Table 1: Simulated Lightweight Material Strategies

Material Strategy	Principal Material Architecture	Primary Benefit	Main Sustainability Constraint
M1: Conventional Metal-Dominant	High-strength steel with limited lightweight alloy substitution	Established manufacturing, repair and recycling	Higher structural mass
M2: GFRP Hybrid Lightweight	Glass-fiber polymer components integrated with metallic load paths	Moderate weight reduction at accessible cost	Matrix recycling and mixed-material separation
M3: Recycled/Bio-Composite	Natural fibers, recycled reinforcement and thermoplastic matrices	Renewable/recycled content and lower-density construction	Durability, variability and structural qualification
M4: Circular Hybrid Composite System	Targeted virgin high-performance reinforcement combined with recycled/bio reinforcement and recyclable matrix	High structural efficiency with circular material allocation	Design complexity and industrial integration

.

15.2 Evaluation Dimensions

- Each material architecture was evaluated using five normalized dimensions on a synthetic 0–100 scale.
- Mass Efficiency represented structural function relative to vehicle mass.
- Structural Performance represented strength, stiffness, fatigue, crash, thermal, and durability potential.

- Manufacturing Feasibility represented production time, process maturity, automation, cost, and quality control.
- Life-Cycle Sustainability represented raw-material, manufacturing, use-phase, and end-of-life considerations.

15.3 Composite Sustainable Mobility Score

The Composite Sustainable Mobility Score was defined as:

[CSMS = 0.20M + 0.25S + 0.20F + 0.20L + 0.15C]

where:

- (M) = Mass Efficiency
- (S) = Structural Performance
- (F) = Manufacturing Feasibility
- (L) = Life-Cycle Sustainability
- (C) = Circularity

Structural performance receives the largest weighting because lightweight materials cannot be considered viable if they fail the functional or safety requirements of the mobility application.

16. Results

Table 2: Simulated Performance of Lightweight Mobility Material Strategies

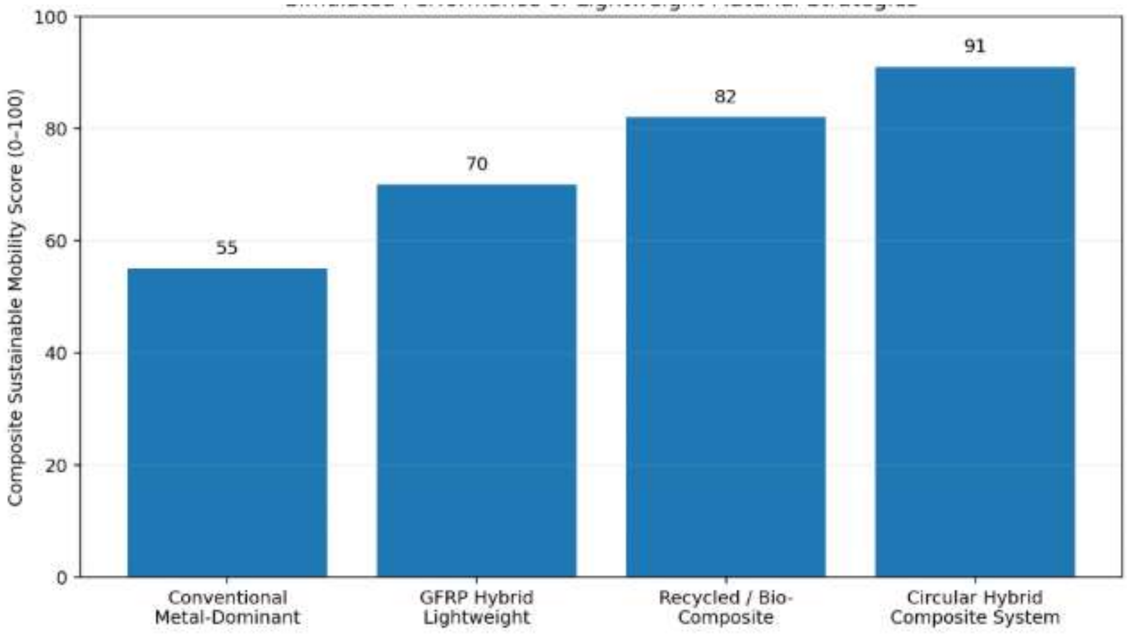
Evaluation Dimension	Metal-Dominant	GFRP Hybrid	Recycled/Bio-Composite	Circular Hybrid Composite
Mass Efficiency	48	72	79	94
Structural Performance	88	82	71	92
Manufacturing Feasibility	92	78	69	84
Life-Cycle Sustainability	42	61	88	93
Circularity	58	52	84	94
Composite Sustainable Mobility Score	**55**	**70**	**82**	**91**

Note: All numerical values are synthetic. They do not represent measured vehicle, material, LCA, or manufacturing data.

The conventional metal-dominant architecture achieves high structural and manufacturing scores because metallic automotive systems have established production and recycling pathways. Its lower composite score results primarily from the assumed mass and life-cycle limitations.

17. Graphical Analysis

Graph 1: Simulated Performance of Lightweight Material Strategies



18. Discussion

18.1 Lightweight Does Not Automatically Mean Sustainable

- The primary finding of the study is conceptual.
- Reducing component mass can improve mobility-system efficiency, but environmental performance depends on the material and process used to achieve that reduction.
- Research on innovative lightweight EV components has shown that production-stage impacts can offset use-stage benefits in certain composite solutions.
- This is particularly important as mobility becomes electrified.
- When vehicle operational emissions decline, embodied environmental impacts from batteries, metals, polymers, and composites can represent a larger share of total life-cycle impacts.
- Designers should therefore avoid selecting materials using weight reduction alone.

18.2 Carbon Fiber Should Be Used Strategically

1. Carbon fiber remains extremely valuable where structural requirements justify its high specific performance.
2. However, using continuous virgin CFRP throughout components with moderate loading can create unnecessary environmental and economic burden.
3. The circular hybrid approach proposes a more selective strategy.

4. Continuous high-performance reinforcement can be placed in major load paths, while recycled carbon fiber, glass fiber, or natural fibers support less demanding zones.
5. This approach follows the broader principle of material sufficiency.

18.3 Natural Fibers Are Important but Not Universal Replacements

- Natural fibers provide important opportunities for sustainable mobility, but they should not be marketed as universal replacements for glass or carbon fibers.
- Recent reviews identify significant progress alongside continuing limitations in moisture resistance, interface stability, thermal behavior, mechanical variability, and high-load structural use.
- Applications should therefore be selected according to actual performance requirements.
- Interior, acoustic, trim, semi-structural, and moderate-load parts may represent especially attractive pathways.
- Further material treatments, hybridization, protective coatings, and optimized matrices may expand future structural applications.

19. Conclusion

1. Lightweight composite materials can contribute significantly to sustainable mobility, but their environmental value cannot be evaluated through mass reduction alone.
2. Vehicle lightweighting interacts with material production, manufacturing energy, structural durability, repair, operational efficiency, recycling, and end-of-life recovery.
3. The present simulation demonstrates how these considerations can be combined within a Sustainable Lightweight Composite Decision Framework.
4. The synthetic Composite Sustainable Mobility Score increases from 55 for a conventional metal-dominant architecture to 70 for a GFRP hybrid system, 82 for a recycled/bio-composite approach, and 91 for an integrated circular hybrid composite strategy.
5. These values are illustrative rather than empirical findings.
6. The broader evidence supports the paper's central conclusion: significant mass reduction may not produce a net life-cycle advantage when production impacts are excessive, while natural-fiber, recycled-fiber, thermoplastic, and hybrid approaches can improve environmental performance when they satisfy structural and manufacturing requirements.

The future of lightweight mobility should therefore move away from the question:

“Which material architecture delivers the required mobility function with the lowest defensible life-cycle burden while retaining structural safety, manufacturability, repairability, and material value?”

Sustainable mobility will increasingly depend not merely on innovative lightweight materials but on circular lightweight material systems.

References

1. L. Yan and H. Xu, "Lightweight composite materials in automotive engineering: State-of-the-art and future trends," Alexandria Engineering Journal, vol. 118, pp. 1–10, 2025, doi: 10.1016/j.aej.2024.12.002.
2. W. Zhang and J. Xu, "Advanced lightweight materials for automobiles: A review," Materials & Design, vol. 221, Art. no. 110994, 2022, doi: 10.1016/j.matdes.2022.110994.
3. Wazeer, A. Das, C. Abeykoon, A. Sinha, and A. Karmakar, "Composites for electric vehicles and automotive sector: A review," Green Energy and Intelligent Transportation, vol. 2, no. 1, 2023, Art. no. 100043, doi: 10.1016/j.geits.2022.100043.
4. E. Oh, M. M. Godoy Zúniga, T. B. Nguyen, B.-H. Kim, T. Trung Tien, and J. Suhr, "Sustainable green composite materials in the next-generation mobility industry: Review and prospective," Advanced Composite Materials, 2024, doi: 10.1080/09243046.2024.2348237.
5. S. J. Skosana, C. Khoathane, and T. Malwela, "Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting," Journal of Thermoplastic Composite Materials, vol. 38, no. 2, 2025, doi: 10.1177/08927057241254324.
6. M. Gonçalves, H. Monteiro, and M. Iten, "Life Cycle Assessment studies on lightweight materials for automotive applications—An overview," Energy Reports, vol. 8, pp. 338–345, 2022, doi: 10.1016/j.egyr.2022.01.067.
7. M. Delogu et al., "Innovative composites and hybrid materials for electric vehicles lightweight design in a sustainability perspective," Materials Today Communications, vol. 13, pp. 192–209, 2017, doi: 10.1016/j.mtcomm.2017.09.012.
8. Y. Atescan-Yuksek, A. Mills, D. Ayre, K. Koziol, and K. Salonitis, "Comparative life cycle assessment of aluminium and CFRP composites: The case of aerospace manufacturing," The International Journal of Advanced Manufacturing Technology, vol. 131, pp. 4345–4357, 2024, doi: 10.1007/s00170-024-13241-3.
9. M. Juntikka, D. Engberg, Y. Aitomäki, and T. Hammar, "Life cycle assessment of lightweight natural fibre/PP-composite side skirts for electric trucks," Cleaner Environmental Systems, vol. 20, Art. no. 100393, 2026, doi: 10.1016/j.cesys.2025.100393.
10. Y. S. Türker, F. Özturk, and Y. Öz, "Review of recycling methods of thermoplastic composite materials," Polymer-Plastics Technology and Materials, vol. 63, no. 12, pp. 1693–1713, 2024, doi: 10.1080/25740881.2024.2352148.
11. P. R. Barnett, N. S. Hmeidat, B. Zheng, and D. Penumadu, "Toward a circular economy: Zero-waste manufacturing of carbon fiber-reinforced thermoplastic composites," npj Materials Sustainability, vol. 2, Art. no. 3, 2024.
12. K. Mohanty, S. Vivekanandhan, N. Tripathi, P. Roy, M. R. Snowdon, L. T. Drzal, and M. Misra, "Sustainable composites for lightweight and flame retardant parts for electric vehicles to boost climate benefits: A perspective," Journal of Composites Science and Manufacturing, 2023, Art. no. 100380, doi: 10.1016/j.jcomc.2023.100380.
13. S. Schade et al., "Life cycle impact assessment of different manufacturing technologies for automotive CFRP components," Journal of Cleaner Production, 2020.

14. R. A. Witik et al., “Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling,” Composites Part A: Applied Science and Manufacturing, 2013.
15. C. Alves et al., “Ecodesign of automotive components making use of natural jute fiber composites,” Journal of Cleaner Production, 2010.
16. S. M. Luz et al., “Environmental benefits of substituting talc by sugarcane bagasse fibers as reinforcement in polypropylene composites: Ecodesign and LCA as strategy for automotive components,” Resources, Conservation and Recycling, 2010.