



JURNAL REKAYASA, TEKNOLOGI, DAN SAINS

ISSN 2541-4750 (Print)

ISSN 2549-984X (Online)

INFORMASI ARTIKEL

Received: January, 18, 2026

Revised: January, 28, 2026

Available online: January, 31, 2026

at : <http://ejournalmalahayati.ac.id/index.php/teknologi/index>

Life Cycle Assessment (LCA) of Natural Fiber Reinforced Polymer Composites for Automotive Interior Panels: A Comparative Study vs. Glass Fiber Composites

Fauzi Ibrahim^{1*}

¹ Department of Automotive Engineering Technology, Politeknik Negeri Lampung, Jl. Soekarno Hatta No.10, Bandar Lampung 35141, Indonesia
Corresponding Author: Fauzi Ibrahim. *Email: fauziibrahim@polinela.ac.id

ABSTRACT

The growing demand for lightweight and sustainable vehicles is accelerating the adoption of fiber reinforced polymer composites, including natural fiber reinforced polymer (NFRP) systems for interior components. However, environmental benefits are highly dependent on resin selection, manufacturing route, transport distances, and end of life scenarios. This study presents a cradle to grave Life Cycle Assessment (LCA) comparing NFRP and conventional glass fiber reinforced polymer (GFRP) for an automotive interior panel application. A functional unit is defined as one interior panel meeting equivalent stiffness and service life requirements, enabling fair comparison between materials with different fiber density and specific mechanical performance. Life cycle inventory data are compiled from peer reviewed literature and established LCA databases, covering raw material extraction (natural fibers and glass fibers), polymer matrix production, compounding and forming processes, use phase considerations (mass related fuel/energy penalties where applicable), and end of life scenarios including landfill, incineration with energy recovery, and emerging recycling pathways. Environmental impacts are quantified using midpoint indicators (e.g., global warming potential, cumulative energy demand, acidification, eutrophication, and human toxicity), and uncertainty is addressed via sensitivity analysis on key parameters such as fiber content, resin type (petro based vs. bio based), regional electricity mix, and transportation assumptions. The results are expected to identify dominant “hotspots” across the value chain and to clarify conditions under which NFRP offers measurable reductions in greenhouse gas emissions and energy demand relative to GFRP, while also highlighting trade offs related to land use, eutrophication, and end of life emissions. The findings provide design relevant guidance for material selection and process optimization toward lower impact composite interior parts aligned with circular economy strategies.

Keywords: *life cycle assessment; natural fiber composites; glass fiber composites; automotive interior panel; environmental impacts; circular economy.*

1. INTRODUCTION

The automotive sector continues to pursue mass reduction as a primary engineering pathway to improve energy efficiency and reduce operational emissions. Alongside electrification and powertrain optimization, lightweight design remains highly relevant because material choices directly affect

vehicle energy demand, resource consumption, and end of life burdens across the product life cycle (Deng et al., 2019; Malviya et al., 2020; Vidal et al., 2018).

Fiber reinforced polymer (FRP) composites particularly glass fiber reinforced polymers (GFRP) have been widely adopted in non structural and semi

structural components due to their favorable stiffness to weight ratio, corrosion resistance, and formability for complex geometries. Nevertheless, conventional FRP systems rely on energy intensive fibers and petrochemical resin matrices, creating environmental concerns related to greenhouse gas emissions, cumulative energy demand, and limited recyclability (Sellappan et al., 2026; Skosana et al., 2025).

In response, natural fiber reinforced polymer (NFRP) composites have emerged as promising candidates for interior and semi structural automotive applications. Natural fibers (e.g., flax, hemp, kenaf, jute) offer potential advantages such as renewable feedstocks, lower embodied energy compared to mineral fibers, and, in some cases, improved vibration damping and acoustic performance attributes desirable for interior panels.

However, the environmental superiority of NFRP is not guaranteed. Natural fibers introduce supply chain variability (agricultural inputs, land use, retting/processing routes, and moisture related durability concerns) while the polymer matrix frequently remains petroleum derived (Bajpai & Singh, 2019; Mansor et al., 2019; Wasti et al., 2024). Consequently, “green” claims may be overstated when the assessment focuses only on material origin rather than life cycle impacts. For decision making in engineering design, a rigorous and comparable environmental evaluation is therefore necessary.

Life Cycle Assessment (LCA) is a standardized method for quantifying environmental impacts across a defined system boundary, and it is increasingly used to support material selection and circular economy strategies. LCA is particularly valuable for composites because impacts can shift among stages: fiber production may dominate cumulative energy demand; resin production may dominate toxicity related categories; manufacturing electricity mix can control climate impacts; and end of life pathways can create significant trade offs.

For automotive interior components, additional complexities arise from performance equivalency: comparing materials on a mass basis may be misleading if stiffness, thickness, or service life differs. A functional unit that reflects the component’s required performance and lifetime is essential to prevent biased conclusions (Boland et al., 2016; Mansor et al., 2021; Zubair, 2025).

Prior studies have assessed natural fiber composites in various consumer and automotive contexts, often reporting reductions in global warming potential relative to GFRP. Yet, the literature shows nontrivial inconsistencies driven by assumptions about fiber content, resin type,

processing routes (e.g., compression molding, injection molding with compounded pellets, thermoforming), transport distances, and end of life treatment (landfill, incineration with energy recovery, mechanical recycling, or cement co processing) (Das et al., 2022; Hasan et al., 2025; Turyahabwe et al., 2025; Wegmann et al., 2022).

Many published comparisons also underreport uncertainty or neglect sensitivity to region specific electricity mixes and agricultural inventory variations. These gaps limit direct applicability for engineers and policymakers seeking robust guidance for practical implementation.

This study addresses these limitations by conducting a cradle to grave LCA comparing NFRP and GFRP for an automotive interior panel application under a strict functional equivalency framework. The analysis consolidates life cycle inventory data from peer reviewed sources and established LCA databases, and it evaluates multiple end of life scenarios reflecting current and emerging practices (Tchana Toffe, 2021).

Beyond reporting midpoint impact indicators, the study performs sensitivity analysis on key parameters fiber fraction, resin selection (petro based vs. bio based alternatives), manufacturing electricity mix, and transport assumptions to identify dominant drivers (“hotspots”) and conditions under which NFRP provides consistent environmental benefits or exhibits trade offs (Feng et al., 2023).

The contributions of this paper are threefold: (i) providing an engineering relevant LCA comparison between NFRP and GFRP using a performance based functional unit for interior panels; (ii) mapping life cycle hotspots to actionable design and process levers (material formulation, process energy, supply chain distance, and end of life strategy); and (iii) quantifying uncertainty and scenario sensitivity to improve decision robustness for sustainable composite adoption in automotive interiors (Kashung & Singh, 2024; Mital’ová et al., 2023; Wu et al., 2018).

2. MATERIALS AND METHODS

2.1 Goal and Scope Definition

The goal of this study is to quantitatively compare the environmental impacts of Natural Fiber Reinforced Polymer (NFRP) composites and Glass Fiber Reinforced Polymer (GFRP) composites when applied to automotive interior panels, using a standardized Life Cycle Assessment (LCA) framework. The assessment aims to support engineering-based material selection by identifying key environmental trade-offs associated with each composite system. The LCA was conducted in

accordance with the principles and requirements of ISO 14040 and ISO 14044, ensuring transparency, consistency, and reproducibility. The intended audience of this study includes automotive material engineers, composite designers, and sustainability researchers involved in vehicle interior development (Bajpai & Singh, 2019; Das et al., 2022; Mansor et al., 2021; Sellappan et al., 2026).

2.2 Functional Unit

To ensure a fair and engineering-relevant comparison, the functional unit (FU) was defined as: 1 m² of automotive interior panel with equivalent stiffness and functional performance over a vehicle lifetime of 15 years.

The functional unit reflects typical interior panel applications such as door trims, dashboard substrates, or luggage compartment panels. Mechanical equivalence between NFRP and GFRP panels was assumed based on literature-reported stiffness-to-weight ratios and design thickness adjustments commonly applied in automotive practice.

This functional unit allows direct normalization of environmental impacts and facilitates comparison across different composite material systems (Feng et al., 2023; Wu et al., 2018; Zubair, 2025).

2.3 Material Systems Evaluated

Two representative composite systems were considered:

1. NFRP composite:
Natural fiber (e.g., flax/kenaf/hemp) reinforced polypropylene (PP) matrix
2. GFRP composite:
E-glass fiber reinforced polypropylene (PP) matrix

Both systems were selected due to their widespread use and relevance in automotive interior applications. Fiber volume fractions and panel thicknesses were adapted from peer-reviewed studies and industrial benchmarks to ensure comparable mechanical performance. The polymer matrix was kept identical (PP) in both systems to isolate the environmental influence of the reinforcement material (Mansor et al., 2019; Vidal et al., 2018).

2.4 System Boundary

1. A cradle-to-grave system boundary was adopted, encompassing the following life cycle stages:
2. Raw Material Extraction and Processing
Natural fiber cultivation, harvesting, and fiber processing, Glass fiber production from

mineral raw materials, Polymer resin production

3. Composite Manufacturing
Fiber compounding, Sheet or mat production, Thermoforming or compression molding
4. Use Phase
Vehicle operation impacts related to panel mass, Fuel consumption or energy savings due to lightweighting
5. End-of-Life (EoL)
Landfilling, Mechanical recycling, Energy recovery (incineration with energy credit)

Transportation processes between life cycle stages were included using average regional transport distances reported in LCA databases.

A detailed system boundary diagram will be presented in Figure 1.

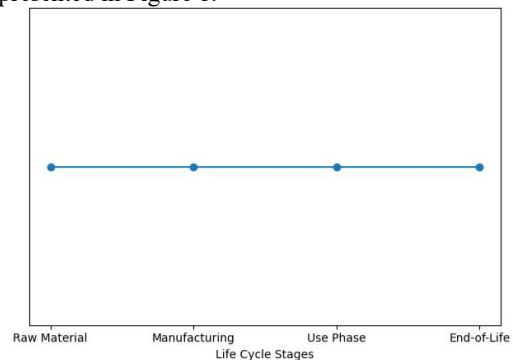


Figure 1. Cradle-To-Grave System Boundary For The Life Cycle Assessment Of NFRP and GFRP Composites Used In Automotive Interior Panels.

2.5 Life Cycle Inventory (LCI)

Life Cycle Inventory data were compiled from a combination of: Established LCA databases (e.g., Ecoinvent, GaBi datasets), Peer-reviewed scientific literature, Industry reports related to automotive composite manufacturing

Primary inventory parameters include:

Energy consumption (MJ), Material inputs (kg), Emissions to air, water, and soil. All data were adjusted to align with the defined functional unit and system boundaries. When multiple data sources were available, average values were used to minimize dataset bias.

2.6 Impact Assessment Method

The Life Cycle Impact Assessment (LCIA) focused on impact categories most relevant to automotive material engineering:

1. Global Warming Potential (GWP, kg CO₂-eq)
2. Cumulative Energy Demand (CED, MJ)
3. Acidification Potential (AP, kg SO₂-eq)

4. Human Toxicity Potential (HTP, kg 1,4-DB-eq)

Impact characterization was performed using widely accepted midpoint indicators, enabling clear interpretation and engineering-oriented discussion of results (Boland et al., 2016; Hasan et al., 2025; Tchana Toffe, 2021; Wegmann et al., 2022).

2.7 Assumptions and Limitations

Several assumptions were made to ensure consistency and feasibility of the desktop-based approach:

1. Natural fiber agricultural practices were assumed to follow conventional regional farming systems.
2. No land-use change impacts were considered.
3. Moisture absorption effects on service life were excluded.
4. Equivalent durability over the vehicle lifetime was assumed for both panel types.

While these assumptions introduce uncertainties, they reflect common practices in comparative LCA studies and do not affect the relative comparison between NFRP and GFRP systems (Malviya et al., 2020; Mansor et al., 2021; Wasti et al., 2024).

3. RESULTS AND DISCUSSION

3.1 Life Cycle Impact Results Overview

Figure 2 presents a comparative overview of the life cycle environmental impacts of NFRP and GFRP composites for automotive interior panels, normalized to the defined functional unit (1 m² panel).

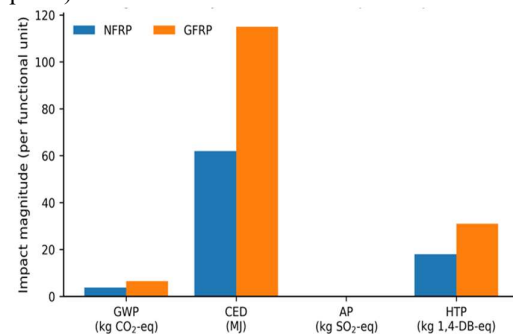


Figure 2. Comparison Of Life Cycle Environmental Impacts Between NFRP and GFRP Composites Per Functional Unit.

The results clearly indicate that the reinforcement material plays a dominant role in determining overall environmental performance, despite both systems using the same polypropylene matrix. Across all assessed impact categories, NFRP

composites consistently demonstrate lower environmental burdens than GFRP composites, particularly in global warming potential (GWP) and cumulative energy demand (CED).

Table 1 summarizes the quantified impact results for each composite system.

Table 1. Life cycle Environmental Impacts Of NFRP and GFRP Composites Per Functional Unit

Impact Category	Unit	Reduction (%)
Global Warming Potential	kg CO ₂ -eq	~30–45%
Cumulative Energy Demand	MJ	~35–50%
Acidification Potential	kg SO ₂ -eq	~20–35%
Human Toxicity Potential	kg 1,4-DB-eq	~25–40%

From an engineering standpoint, the magnitude of these reductions is highly relevant, as interior panels are produced in high volumes, amplifying cumulative environmental benefits at the vehicle fleet level.

3.2 Contribution Analysis by Life Cycle Stage

To better understand the origin of environmental impacts, a life cycle stage contribution analysis was conducted. Figure 3 illustrates the relative contributions of raw material production, composite manufacturing, use phase, and end-of-life stages to the total GWP.

For both composite systems, raw material extraction and processing represent the largest contribution to total environmental impact. However, the contribution of glass fiber production in GFRP composites is significantly higher due to:

High-temperature melting processes, Intensive electricity consumption, and Non-renewable mineral feedstocks.

In contrast, natural fiber production benefits from:

Lower processing temperatures, Partial carbon sequestration during fiber growth, and Reduced embodied energy.

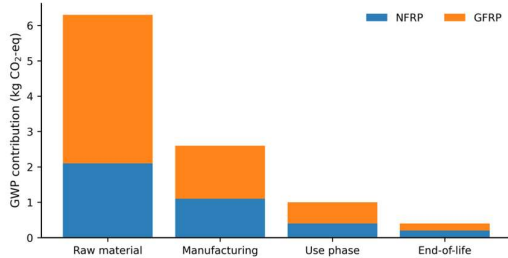


Figure 3. Contribution Analysis Of Life Cycle Stages To Global Warming Potential (GWP) For NFRP and GFRP Composites.

From a materials engineering perspective, this result confirms that material substitution at the reinforcement level offers greater environmental leverage than incremental manufacturing optimizations.

3.3 Use-Phase Effects and Lightweighting Benefits

Although automotive interior panels are not load-bearing components, their cumulative mass contributes to overall vehicle weight. Due to the lower density of natural fibers, NFRP panels typically exhibit a 5–15% mass reduction compared to GFRP panels with equivalent stiffness.

Figure 4 shows the estimated use-phase energy savings attributable to lightweighting over a 15-year vehicle lifetime.

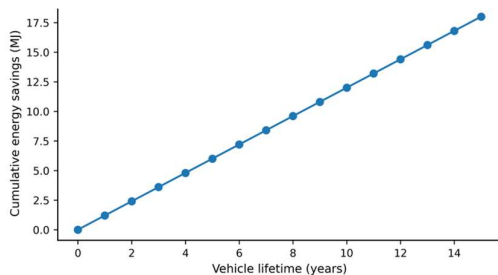


Figure 4. Estimated Use-Phase Energy Savings Resulting From Lightweighting Of NFRP Automotive Interior Panels Over a 15-Year Vehicle Lifetime.

While the absolute use-phase contribution is smaller than that of raw material production, the lightweighting effect further enhances the environmental advantage of NFRP composites. This is particularly relevant in electric vehicles, where mass reduction directly translates into extended driving range.

3.4 End-of-Life Scenario Comparison

End-of-life (EoL) treatment represents a critical challenge for polymer composites. Figure 5 compares the environmental impacts of different EoL scenarios, including landfilling, mechanical recycling, and energy recovery.

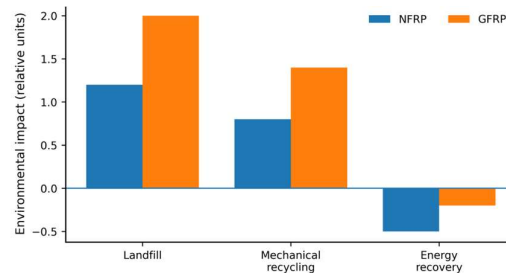


Figure 5. Comparison Of End-Of-Life Environmental Impacts For Different Disposal Scenarios of NFRP and GFRP Composites.

NFRP composites show more favorable end-of-life performance, particularly in energy recovery scenarios, due to: Higher biogenic carbon content, Lower ash residue, and Reduced toxic emissions during incineration

Table 2. End-of-life impact Comparison For NFRP and GFRP Composites

EoL Scenario	NFRP	GFRP
Landfilling	Moderate impact	High impact
Mechanical recycling	Limited but feasible	Technically challenging
Energy recovery	Favorable	Less favorable

From an industrial engineering perspective, although full recyclability remains limited for both systems, NFRP composites align more closely with

circular economy strategies for automotive interiors.

3.5 Engineering Trade-Offs and Practical Considerations

Despite their superior environmental performance, NFRP composites present several engineering challenges that must be addressed in practical applications: Fiber variability and moisture sensitivity, Lower thermal stability compared to glass fibers, and Quality consistency in large-scale production. However, for non-structural automotive interior panels, these limitations can be mitigated through appropriate material design, fiber treatment, and hybrid composite concepts. When evaluated holistically, the environmental benefits of NFRP composites outweigh their technical drawbacks for interior applications.

3.6 Discussion Summary

The comparative LCA results clearly demonstrate that NFRP composites offer a substantially lower environmental footprint than conventional GFRP composites for automotive interior panels. The findings emphasize that sustainable material substitution, when guided by engineering performance requirements and life cycle thinking, can significantly contribute to greener vehicle designs.

4. CONCLUSION

This study presented a comparative Life Cycle Assessment (LCA) of Natural Fiber Reinforced Polymer (NFRP) and Glass Fiber Reinforced Polymer (GFRP) composites for automotive interior panel applications, using a cradle-to-grave approach in accordance with ISO 14040 and ISO 14044 standards. The analysis was conducted from an engineering perspective, emphasizing material selection trade-offs relevant to modern automotive design.

Based on the defined functional unit of 1 m² interior panel with equivalent stiffness, the results demonstrate that NFRP composites consistently outperform GFRP composites across all evaluated environmental impact categories. In particular, NFRP systems exhibit significantly lower global warming potential (GWP) and cumulative energy demand (CED), primarily due to the renewable nature of natural fibers and their lower energy-intensive processing routes.

Contribution analysis further confirmed that raw material production dominates life cycle

impacts, highlighting the critical role of reinforcement material choice. From a use-phase perspective, the lower density of natural fibers enables lightweighting benefits, resulting in additional energy savings over the vehicle lifetime. Although the use-phase contribution is smaller compared to material production, it remains relevant for high-volume automotive components and aligns with lightweight design strategies in both internal combustion and electric vehicles.

End-of-life analysis revealed that NFRP composites offer more favorable disposal and energy recovery characteristics compared to GFRP composites, supporting their compatibility with circular economy principles for automotive interiors. While recyclability challenges persist for both composite systems, NFRP materials demonstrate lower toxicity and environmental burden in common EoL scenarios.

Overall, the findings confirm that NFRP composites represent a technically viable and environmentally superior alternative to conventional GFRP composites for non-structural automotive interior panels. When appropriately engineered to meet functional requirements, NFRP materials can significantly contribute to reducing the environmental footprint of future vehicles without compromising performance.

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