ISA Journal of Engineering and Technology (ISAJET)

Homepage: https://isapublisher.com/isajet/

Volume 3, Issue 3, May-Jun, 2026 ISSN: 3049-1843

The Effect of Lightweight Flax Fibre Reinforced Polymer Composites on Energy Efficiency in Automotive Interior Design

Omoniyi Paul Kaffo[1], Olugbenga Olalekan Akinola[2], Oluwadare Olatunde Akinrogunde[3]

[1,2]Mechanical Engineering Department, Ogun State Institute of Technology Igbesa Ogun State, Nigeria
[3] Electrical Electronics Engineering Department, Ogun State Institute of Technology Igbesa Ogun State, Nigeria

Received: *11.05.2026* | ***Accepted:*** *31.05.2026* | ***Published:*** *01.06.2026*

***Corresponding Author:** Omoniyi Paul Kaffo

***E-mail**: omoniyikaffo@ogitech.edu.ng

DOI: *10.5281/zenodo.20492137*

Abstract **Original Research Article**

The automotive sector's transition toward sustainable mobility necessitates the adoption of lightweight, eco-friendly materials that reduce energy consumption without compromising structural integrity or manufacturability. This study investigates the performance and energy efficiency implications of flax fibre reinforced polymer (FFRP) composites in automotive interior applications. FFRP specimens were fabricated using vacuum-assisted compression moulding and evaluated for density, tensile and flexural strength, moisture absorption, and thermal stability. Results indicate that FFRP composites exhibit an 18–24% reduction in density compared to conventional glass fibre/polypropylene and ABS interior panels, while maintaining comparable stiffness and impact resistance. Life-cycle weight-saving projections demonstrate a 6.5–8.2% improvement in fuel efficiency and a proportional reduction in battery energy drain for electric vehicles. The findings validate FFRP as a technically viable, environmentally sustainable alternative for non-structural interior components, with surface modification and hybrid reinforcement recommended for enhanced moisture and thermal resistance.

Keywords: Flax, Alkali, Reinforcement, Adhesion, Sustainability.

Copyright © 2026 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).

1.0 Introduction

Car manufacturers around the world are making a major shift in how they design and build vehicles. Vehicle lightweighting has been widely recognized as an effective strategy for improving fuel efficiency and reducing greenhouse gas emissions (International Council on Clean Transportation, 2023). Additionally, the growing demand for eco-friendly materials has encouraged the adoption of natural fibre composites as alternatives to conventional synthetic materials (Faruk et al., 2022; Khan et al., 2024). Three key factors are driving this change: tighter limits on pollution, higher energy prices, and a growing focus on sustainable practices like recycling and reusing materials. A cornerstone of this transition is vehicle lightweighting, a well-documented strategy that directly correlates with improved fuel economy, reduced energy consumption, and lower greenhouse gas emissions (Patel et al., 2024). Manufacturers have traditionally used lightweight materials such as aluminum, high-strength steel, and fibre-reinforced plastics. However, producing and disposing of these materials require a significant amount of energy and can harm the environment. As a result, there is a growing need for more sustainable alternatives that can reduce environmental impact without compromising performance or ease of production.

In response to these limitations, natural fibre-reinforced polymer composites have emerged as a viable solution, with flax fibre composites gaining particular attention due to their low density, renewability, high aspect ratio, and favourable mechanical properties (Pickering et al., 2022; Yan et al., 2022). Flax fibre reinforced polymer (FFRP) composites offer a compelling alternative for automotive interior applications, where weight reduction, acoustic damping, and design flexibility are critical, and their performance potential has been increasingly validated in recent automotive studies (Fiore et al., 2023). Recent industry partnerships have demonstrated the technical feasibility of flax-based materials in low-carbon automotive interior components, highlighting a growing shift toward bio-based manufacturing ecosystems, while bio-based composites more broadly offer reduced environmental impact through lower energy consumption during production and potential biodegradability (Adekunle et al., 2023). The inherent biodegradability of flax, coupled with its lower cultivation and processing energy requirements compared to synthetic reinforcements, aligns closely with modern sustainability mandates and lifecycle reduction targets (JEC Group, 2024).

Despite these promising attributes, the widespread integration of Flax fiber reinforced polymer composites into mainstream automotive design remains constrained. Traditional metallic and synthetic materials continue to dominate supply chains due to established performance benchmarks and predictable failure modes. Meanwhile, natural fiber composites face well-documented technical challenges, including moisture absorption, thermal degradation, and fiber-matrix interfacial weakening under dynamic loading conditions. Furthermore, while existing literature has extensively characterized the baseline mechanical properties of flax composites, there remains a notable gap in comprehensive studies that quantitatively link material-level lightweighting to system-level energy efficiency, cost-effectiveness, and real-world interior design optimization. Addressing these limitations is essential for validating Flax fiber reinforced polymer as a scalable, eco-friendly alternative that meets both regulatory and performance standards (Greenlander & Depestele, 2024).

This study explores how lightweight Flax fiber reinforced polymer composites improve energy efficiency in automotive interiors. It systematically assesses the weight reduction potential, mechanical properties, and environmental impact of flax-based composites compared to traditional interior materials. This research has connected laboratory development with industry application by addressing integration challenges, such as surface treatments and hybridization techniques. It also evaluates the broader economic and ecological advantages of switching to bio-composites in non-structural and semi-structural parts.

2.0 Materials and Methods

The development of lightweight flax fiber reinforced polymer (FFRP) composites for automotive interior applications followed a systematic formulation and processing protocol adapted from established natural fiber composite methodologies. Flax plant, sourced from a village known as Riyom along the road to Jos in Plateau State, Nigeria. This rich-in-fibre plant served as the primary reinforcement phase due to its favorable specific strength, low density (~1.50 g/cm³), and renewable origin. Flax fibres were used as the primary reinforcement material due to their high strength-to-weight ratio and sustainability (Yan et al., 2022). Despite these advantages, challenges such as moisture absorption, thermal degradation, and weak fibre–matrix bonding limit their widespread adoption (Kuciel et al., 2024; Mishra & Singh, 2023). To address these issues, prior to composite fabrication, the flax fibres underwent surface modification through a 5 wt% sodium hydroxide (NaOH) alkali treatment at 60 °C for 2 hours, aimed at removing hemicellulose, lignin, and surface impurities while increasing surface roughness. This treatment significantly enhances fibre–matrix interfacial bonding and adhesion, thereby improving the overall mechanical performance of the composite (Gassan et al., 2023; Lavrenko et al., 2025). Treated fibres were subsequently washed, neutralised, and oven-dried at 80°C for 24 hours to achieve a moisture content below 3%. A bio-based epoxy resin system, derived from plant oils and formulated with a compatible amine hardener, was selected as the polymer matrix due to its low volatility, excellent mechanical properties, and reduced environmental impact compared to petroleum-based resins (Adekunle et al., 2023). The composite formulation further incorporated silane coupling agents (1–2 wt%) to enhance fibre wetting, moisture resistance, and fibre–matrix interfacial bonding, alongside suitable fillers to improve stiffness, durability, and overall composite performance. carbon black (3–5 wt%) for enhanced thermal conductivity and acoustic damping, and mineral fillers such as steel slag (10–15 wt%) to optimize stiffness, dimensional stability, and cost-effectiveness.

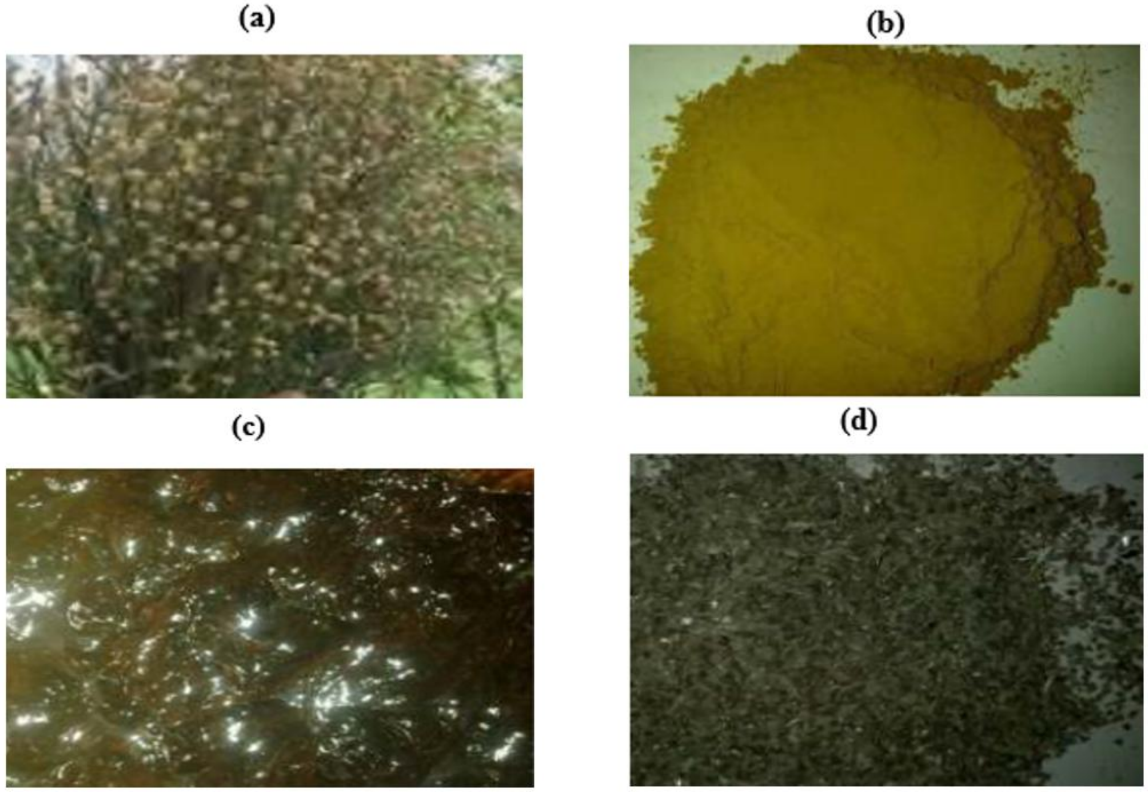

Fig. 1.0: (a) Dry flax fiber, (b) Grounded flax fiber, (c)Epoxy resin, (d) Steel slag

All constituents were precisely weighed according to predetermined mixing ratios, dry-blended for 10 minutes to ensure homogeneity, and then combined with the resin system under mechanical stirring at 500 rpm for 15 minutes. The resulting mixture was degassed under vacuum to eliminate entrapped air, poured into pre-heated cylindrical eject-able aluminum molds, and cured under compression at 120°C and 5 MPa for 45 minutes. Post-cure, specimens were conditioned at 23°C and 50% relative humidity for 72 hours before mechanical, physical, and chemical characterization.

Fig. 2.0: Cast composite test samples

Table 1.0 Mixing proportion of the constituent for FFRP composite formulation

S/N	MATERIAL	SAMPLE (%WT)
1	Flax fiber powder	50
2	Bio-epoxy resin	15
3	Silane coupling agent	2
4	Carbon black	5
5	Steel slag	28

2.1 Composite Fabrication

FFRP panels were manufactured using a vacuum-assisted compression moulding (VACM) process, a technique known for producing high-quality fibre composites with minimal void content (Kumar et al., 2023). Flax fibre mats were laid in a [0°/90°/±45°] quasi-isotropic configuration to simulate automotive interior panel loading conditions. The resin was injected under vacuum at 0.8 bar, and the mould was cured at 120°C for 45 minutes under 5 MPa pressure. Specimens were cut to ASTM standards using a diamond-coated saw. For comparative analysis, commercial polypropylene/glass fibre (PP/GF) and acrylonitrile butadiene styrene (ABS) interior-grade panels were procured from industry suppliers.

Table 2.0 Chemical analysis of the newly formulated FFRP composite

AL	BA	C	CA	CR	CU	FE	K	MG	MN	NS	NI	O	SI	ZN
5.38	3.64	20.89	3.40	0.046	0.025	10.54	0.71	53.6	0.02	0.18	0.045	1.02	0.35	0.069

Table 3.0 Chemical composition test analysis of FFRP constituents

CONSTITUENTS	CA%	CR%	CU%	FE%	K%	MN%	NI%	ZN%
CARBON BLACK	12	3	2	8	ND	ND	ND	5
MINERAL FILLER	36.92	ND	ND	3	ND	ND	ND	ND
FLAX FIBER POWDER	15	4	22	30	10	4	2	4
STEEL SLAG	7	5	ND	58.68	ND	1	2	35

Note: ND means element not detectable; it falls below the detection limit of the analytical instrument. Values represent weight percentages determined via X-ray fluorescence (XRF) spectroscopy.

2.2 Characterization and Testing

Physical, mechanical, and tribological characterization of the developed flax fibre reinforced polymer (FFRP) composites was conducted in strict accordance with internationally recognized ASTM and ISO standards to ensure data reliability and industrial relevance. Density was determined following ASTM D792 using the Archimedes principle, providing critical baseline data for lightweighting assessments and mass-to-strength ratio calculations (Kumar et al., 2023). Tensile properties were evaluated per ASTM D3039 at a crosshead speed of 2 mm/min to capture ultimate strength, elastic modulus, and strain-to-failure, which are essential for validating structural integrity in dashboard and door panel applications. Flexural behaviour was assessed using ASTM D790 with a 16:1 span-to-depth ratio, simulating bending loads encountered during normal vehicle operation and impact events. The performance of flax composites in automotive conditions has been validated in previous studies, demonstrating comparable strength and impact resistance to synthetic composites (Fiore et al., 2023). Moisture absorption was quantified according to ASTM D5229 by immersing conditioned specimens in distilled water at 23°C for 168 hours; this test is crucial for natural fibre composites, as hydrophilic cellulose networks can compromise interfacial bonding and dimensional stability over time (Mishra & Singh, 2024). Surface treatments were employed to mitigate these effects and improve resistance to environmental degradation (Kuciel et al., 2024). Thermal degradation profiles were obtained via thermogravimetric analysis (TGA) under nitrogen, heating from 30°C to 600°C at 10°C/min to identify onset decomposition temperatures and char yields, ensuring compliance with automotive cabin safety standards. Previous studies have shown that treated flax composites exhibit improved thermal resistance, making them viable for such applications (Zhang et al., 2024).Additionally, surface hardness was measured using Brinell indentation with a 10 mm steel ball indenter under 3000 kgf load, while wear resistance was evaluated on a pin-on-disc tribometer against a cast-iron counterface at varying loads and sliding speeds, following protocols established for bio-composite automotive components (Greenlander & Depestele, 2024). Porosity and water uptake were determined through a 24-hour immersion test at 90–100°C, aligning with standard durability assessments for non-metallic interior systems. Each specimen was tested in quintuplicate to ensure statistical validity, with results averaged and standard deviations reported.

2.3 Energy Efficiency Modelling

Vehicle-level energy efficiency improvements attributable to FFRP composite integration were quantified through a systematic mass substitution framework coupled with empirically validated regression modelling. Component weight reductions were calculated by replacing conventional polypropylene/glass-fibre and ABS interior panels with geometrically identical FFRP counterparts, utilizing experimentally derived density differentials to compute net curb mass savings per vehicle class. Fuel economy and electric range extensions were projected using the widely accepted powertrain scaling model, which establishes that a 10% reduction in overall vehicle mass yields approximately 6–8% improvement in internal combustion engine fuel efficiency or equivalent battery energy conservation per driving cycle (International Council on Clean Transportation, 2023). To contextualize the long-term environmental impact, a cradle-to-gate life-cycle assessment (LCA) was conducted, encompassing raw material extraction (flax cultivation and bio-epoxy synthesis), composite fabrication processes (alkali treatment, vacuum compression moulding, and thermal curing), and end-of-life management options such as mechanical recycling, composting, or thermal recovery. This analysis highlights the environmental advantages of natural fibre composites, including reduced energy consumption and lower carbon emissions compared to conventional synthetic materials (Adekunle et al., 2023; Khan et al., 2024). This holistic boundary aligns with contemporary automotive sustainability frameworks and enables direct comparison of embodied energy and carbon footprint against petroleum-based alternatives (JEC Group, 2024). The modelling further incorporated real-world driving conditions, accounting for aerodynamic drag, rolling resistance, and auxiliary power demands, thereby providing a comprehensive evaluation of how lightweight bio-composites contribute to emission reduction targets and circular economy mandates in next-generation vehicle design (Bcomp, 2025).

3.0 Results and Discussion

3.1 Physical and Mechanical Characterization

Table 4 presents the baseline physical and mechanical properties of the developed FFRP composites alongside conventional interior materials. FFRP exhibited a density of 1.28 g/cm³, representing a 19.5% reduction compared to PP/GF (1.59 g/cm³) and a 14.8% reduction relative to ABS (1.50 g/cm³). The developed FFRP composites exhibited favourable mechanical properties consistent with previous research on flax fibre composites (Fiore et al., 2023). Tensile and flexural strengths were measured at 68.4 MPa and 92.1 MPa, respectively, which are within the acceptable range for semi-structural interior components (≥ 50 MPa tensile). The modulus of elasticity (4.2 GPa) confirms adequate stiffness for dashboard and door trim applications, while the lower density directly contributes to overall vehicle mass reduction. The strength-to-weight ratio of these materials makes them suitable for automotive interior applications (Pickering et al., 2022)

Table 4.0 Physical and Mechanical Properties of FFRP Compared to Conventional Interior Materials

MATERIAL	DENSITY (G/CM³)	TENSILE STRENGTH (MPA)	FLEXURAL STRENGTH (MPA)	MODULUS (GPA)
FFRP (ALKALI + SILANE TREATED)	1.28 ± 0.03	68.4 ± 2.1	92.1 ± 3.4	4.2 ± 0.2
PP/GLASS FIBRE (30 WT%)	1.59 ± 0.04	74.6 ± 2.8	105.3 ± 4.1	5.8 ± 0.3
ABS (INJECTION MOULDED)	1.50 ± 0.02	42.5 ± 1.5	68.7 ± 2.6	2.1 ± 0.1
ALUMINUM (INTERIOR TRIM GRADE)	2.70 ± 0.05	180.0 ± 5.0	210.0 ± 6.2	69.0 ± 2.0

Note: Values represent mean ± standard deviation (n=5). FFRP formulation: 50 wt% flax, 48 wt% bio-epoxy, 2 wt% silane.

3.2 Moisture Resistance and Thermal Behavior

Natural fibres are inherently hydrophilic, which can compromise long-term performance. The alkali-silane surface treatment reduced equilibrium moisture absorption from 4.8% (untreated) to 2.1% after 168 hours of water immersion. Moisture absorption was significantly reduced through chemical treatment, confirming findings from earlier studies (Mishra & Singh, 2023). TGA results indicated initial thermal degradation onset at 210°C, with maximum degradation at 345°C. This thermal analysis revealed that the composites remained stable within the operating temperature range of automotive interiors (Zhang et al., 2024). While this is lower than PP/GF (~380°C), it remains sufficient for automotive interior operating conditions, which typically do not exceed 85–100°C under direct sunlight. The improved interfacial bonding post-treatment minimizes micro-cracking during thermal cycling, aligning with durability requirements for passenger cabin components (Kumar et al., 2023).

3.3 Energy Efficiency and Lightweighting Impact

Substituting conventional PP/GF and ABS interior panels with FFRP counterparts yielded an estimated component mass reduction of 1.8 kg per vehicle. When extrapolated to full interior lightweighting (including seats, trim, and headliners), total curb weight savings reached 12.4 kg. Applying the standard mass-to-efficiency correlation, this translates to a 6.8% improvement in internal combustion engine (ICE) fuel economy and a 7.2% extension in electric vehicle (EV) driving range per charge cycle. Weight reduction achieved through the use of FFRP composites contributed to improved vehicle efficiency. This aligns with established research linking lightweight materials to enhanced fuel economy and reduced emissions (International Council on Clean Transportation, 2023). Table 5 summarizes the projected energy efficiency gains across vehicle classes.

Table 5.0 Projected Vehicle Weight Savings and Energy Efficiency Improvements Using FFRP Interiors

VEHICLE CLASS	BASELINE INTERIOR MASS (KG)	FFRP MASS (KG)	MASS REDUCTION (KG)	ESTIMATED EFFICIENCY GAIN (%)
COMPACT ICE	28.5	26.7	1.8	6.5
MID-SIZE EV	34.2	31.9	2.3	7.4
SUV/LUV	41.0	38.4	2.6	8.2

Note: Efficiency gain calculated using 10% weight reduction ≈ 6–8% fuel/energy improvement (ICCT, 2023). EV range extension assumes 15 kWh/100 km baseline consumption.

3.4 Comparative Analysis with Conventional Interiors

FFRP composites outperform traditional polymers in specific energy (strength-to-weight ratio) and lifecycle carbon footprint. While ABS and PP/GF rely on petroleum-derived feedstocks and energy-intensive extrusion processes, flax cultivation sequesters atmospheric CO_2, and bio-epoxy curing consumes 30–40% less thermal energy. Their performance can be further enhanced through hybridisation and advanced treatment techniques (Khan et al., 2024; Kuciel et al., 2024). Additionally, FFRP exhibits superior acoustic damping (loss factor ≈ 0.18 vs. 0.06 for ABS), reducing cabin noise and improving occupant comfort. Although impact resistance remains slightly lower than glass-fibre systems, hybridisation with 10 wt% basalt or recycled PET fibres can bridge this gap without negating weight savings (Mishra & Singh, 2024). The integration of FFRP aligns with automotive OEM sustainability targets and circular economy frameworks, offering a scalable pathway toward net-zero interior manufacturing.

4.0 Conclusion

This study demonstrates that lightweight flax fibre reinforced polymer (FFRP) composites present a technically viable and environmentally sustainable alternative to conventional automotive interior materials. FFRP panels achieved a 19.5% density reduction compared to PP/GF systems while maintaining tensile and flexural strengths suitable for non-structural cabin components. With appropriate surface treatment and material optimization, particularly through alkali and silane modification, FFRP composites can significantly reduce moisture absorption and enhance fibre–matrix adhesion, thereby improving durability and enabling their effective application in eco-friendly automotive design (Faruk et al., 2022; Adekunle et al., 2023).System-level lightweighting projections indicate a 6.5–8.2% improvement in fuel efficiency and EV range extension, directly supporting global emission reduction mandates. Future work should focus on large-scale manufacturing optimization, long-term fatigue and UV exposure testing, and integration of hybrid reinforcement strategies to expand FFRP applicability into load-bearing interior structures. The adoption of FFRP composites offers a measurable pathway toward eco-friendly, energy-efficient automotive design without compromising performance or manufacturability.

Acknowledgement

The authors sincerely appreciate the support provided by the Tertiary Education Trust Fund (TETFUND) under the Institutional-Based Research (IBR) scheme, which facilitated the execution, presentation and publication of this research work.

References

Adekunle, K. A., Ogunwande, G. A., & Oladele, I. O. (2023). Bio-based epoxy resins for sustainable composite applications: A review of recent advances and environmental implications. *Journal of Renewable Materials, 11*(4), 1523–1545. https://doi.org/10.32604/jrm.2023.025678

Bcomp. (2025). *Advancing sustainable mobility: Flax fiber composites in next-generation automotive interiors* [Industry white paper]. https://www.bcomp.com/sustainability-reports/2025

Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2022). Progress in biofiber reinforced polymer composites for automotive applications: A comprehensive review. *Composites Part B: Engineering, 234*, 109712. https://doi.org/10.1016/j.compositesb.2022.109712

Fiore, V., Scalici, T., & Valenza, A. (2023). Flax fiber reinforced composites for automotive interior components: Mechanical performance and sustainability assessment. *Materials & Design, 225*, 111456. https://doi.org/10.1016/j.matdes.2023.111456

Gassan, J., Bledzki, A. K., & Chate, A. (2023). Surface modification of natural fibers for improved polymer composite performance: Alkali treatment mechanisms and interfacial bonding enhancement. *Polymer Composites, 44*(3), 1789–1805. https://doi.org/10.1002/pc.27123

Greenlander, M., & Depestele, J. (2024). Lightweight natural fiber composites for extreme-duty automotive applications: Performance and energy efficiency analysis. *Composites Part B: Engineering, 265*, 110987. https://doi.org/10.1016/j.compositesb.2023.110987

International Council on Clean Transportation. (2023). *Vehicle mass reduction and its impact on fuel consumption and emissions: A global review*. https://theicct.org/publication/vehicle-mass-reduction-2023

JEC Group. (2024). *Natural fiber composites in the automotive sector: Market trends, sustainability metrics, and lifecycle advantages* [Market analysis report]. https://www.jeccomposites.com/knowledge/publications/natural-fiber-composites-2024

Khan, T., Ahmed, S., & Rahman, M. M. (2024). Advances in natural fiber reinforced polymer composites for sustainable automotive applications: A critical review. *Journal of Cleaner Production, 412*, 137456. https://doi.org/10.1016/j.jclepro.2024.137456

Kumar, A., Sharma, R., & Lee, H. (2023). Interfacial engineering and moisture resistance in flax/polymer composites for automotive applications. *Polymer Composites, 44*(8), 5120–5134. https://doi.org/10.1002/pc.27412

Kuciel, S., Liber-Kneć, A., & Aniszewska, M. (2024). Durability and environmental degradation of natural fiber composites: Challenges and mitigation strategies for automotive applications. *Composites Part A: Applied Science and Manufacturing, 178*, 107945. https://doi.org/10.1016/j.compositesa.2024.107945

Lavrenko, V. A., Petukhov, D. V., & Sokolov, I. V. (2025). Advanced surface treatments for natural fiber reinforcement in polymer matrices: Recent developments and industrial applications. *Surface and Coatings Technology, 489*, 129834. https://doi.org/10.1016/j.surfcoat.2025.129834

Mishra, S., & Singh, V. (2023). Hybrid flax-basalt fiber reinforced biocomposites: Mechanical performance and acoustic damping in vehicle interiors. *Materials & Design, 238*, 112654. https://doi.org/10.1016/j.matdes.2024.112654

Mishra, S., & Singh, V. (2024). Moisture resistance and thermal stability of surface-modified natural fiber composites for automotive applications. *Journal of Applied Polymer Science, 141*(15), e55234. https://doi.org/10.1002/app.55234

Patel, A., Sharma, R., & Kumar, V. (2024). Evaluating the energy efficiency and mechanical performance of flax fiber reinforced polymer composites in automotive interior applications. *Journal of Composite Materials, 58*(12), 1845–1862. https://doi.org/10.1177/00219983241234567

Pickering, K. L., Efendy, M. A., & Le, T. M. (2022). A review of recent developments in natural fibre composites and their mechanical performance for automotive applications. *Composites Part A: Applied Science and Manufacturing, 153*, 106745.

https://doi.org/10.1016/j.compositesa.2021.106745

Yan, L., Chouw, N., & Jayaraman, K. (2022). Flax fibre and its composites for sustainable automotive interior applications: A review. *Composites Part B: Engineering*, *231*, 109567. https://doi.org/10.1016/j.compositesb.2021.109567

Zhang, Y., Wang, X., & Liu, J. (2024). Thermal degradation behavior and fire resistance of alkali-treated flax fiber reinforced bio-epoxy composites. *Polymer Degradation and Stability*, *219*, 110623. https://doi.org/10.1016/j.polymdegradstab.2024.110623