

A STRUCTURED ENGINEERING REVIEW AND MULTI-CRITERIA ASSESSMENT OF BIO-BASED RESINS FOR AUTOMOTIVE COMPOSITES

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Abstract

Automotive composite selection increasingly integrates lightweighting, circularity, and renewable-carbon objectives. Resin choice must therefore be evaluated through mechanical, thermal, durability, manufacturing, and end-of-life requirements rather than renewable content alone. This study presents a structured integrative engineering review and multi-criteria assessment of bio-based matrix routes for automotive composites. The auditable corpus contains 23 sources: 22 peer-reviewed technical studies and four policy or industry sources used only for contextual statements. Technical evidence was coded across eight criteria using an explicit 0-10 rubric: mechanical capability, specific stiffness, thermal window, moisture durability, process readiness, bio-carbon benefit, circularity potential, and supply maturity. Five matrix routes were assessed with author-assigned automotive-design weights and a 100,000-iteration sensitivity analysis in which each weight was varied independently by $\pm 20\%$ and renormalized. Bio-based engineering thermoplastics represented by PA11 and bio-PE achieved the highest base score (7.56), followed by aromatic lignin/vanillin bio-epoxy (7.23) and furan/itaconic thermosets (6.80). The leading route remained first in all simulations, with a 5th-95th percentile interval of 7.51-7.61. The results support near-term use in interior panels, trunk liners, seat backs, acoustic covers, and selected semi-structural parts. Moisture uptake, low glass-transition temperature in flexible systems, fire and smoke compliance, cure time, natural-fiber variability, and end-of-life separation remain the principal validation barriers.

Keywords:

automotive composites; bio-based epoxy; bio-based thermoplastics; multi-criteria assessment; sustainable manufacturing

Abstrak

Pemilihan material komposit otomotif semakin mempertimbangkan pengurangan bobot, sirkularitas, dan penggunaan karbon terbarukan. Oleh karena itu, pemilihan resin perlu dievaluasi berdasarkan persyaratan mekanik, termal, ketahanan, proses manufaktur, dan pengelolaan akhir masa pakai, bukan hanya berdasarkan kandungan bahan terbarukan. Penelitian ini menyajikan tinjauan rekayasa integratif yang terstruktur dan penilaian multikriteria terhadap berbagai jenis matriks berbasis hayati untuk komposit otomotif. Bukti teknis diklasifikasikan ke dalam delapan kriteria menggunakan rubrik penilaian eksplisit berskala 0–10, yaitu kemampuan mekanik, kekakuan spesifik, rentang ketahanan termal, ketahanan terhadap kelembapan, kesiapan proses, manfaat karbon hayati, potensi sirkularitas, dan kematangan pasokan. Lima kelompok matriks dinilai menggunakan bobot yang ditetapkan berdasarkan pertimbangan desain otomotif. Stabilitas hasil pemeringkatan selanjutnya diuji melalui 100.000 iterasi analisis sensitivitas, dengan setiap bobot divariasikan secara independen sebesar $\pm 20\%$ dan dinormalisasi kembali. Termoplastik rekayasa berbasis hayati yang diwakili oleh PA11 dan bio-PE memperoleh skor dasar tertinggi sebesar 7,56, diikuti oleh bio-epoksi aromatik berbasis lignin/vanilin sebesar 7,23 dan termoset berbasis furan/itakonit sebesar 6,80. Kelompok matriks dengan peringkat tertinggi tetap menempati posisi pertama dalam seluruh simulasi, dengan rentang persentil ke-5 hingga ke-95 sebesar 7,51–7,61. Hasil penelitian mendukung pemanfaatan material tersebut dalam jangka pendek pada panel interior, pelapis bagasi, sandaran kursi, penutup akustik, dan sejumlah komponen semistruktural. Namun, penyerapan kelembapan, rendahnya temperatur transisi kaca pada sistem yang fleksibel, pemenuhan persyaratan ketahanan api dan asap, waktu pengerasan, variasi karakteristik serat alam, serta pemisahan material pada akhir masa pakai masih menjadi kendala utama yang memerlukan validasi lebih lanjut.

Kata kunci:

komposit otomotif; bio-epoksi; termoplastik berbasis hayati; penilaian multikriteria; manufaktur berkelanjutan

DOI: [10.38038/vocatech.v8i2.334](https://doi.org/10.38038/vocatech.v8i2.334)

Received: 18 May 2026; Accepted: 22 July 2026; Published: 15 October 2026

Citation in APA Style: Marjuni, T., & Ibrahim, F. (2026). A structured engineering review and multi-criteria assessment of bio-based resins for automotive composites. *VOCATECH: Vocational Education and Technology Journal*, 8(2), 01-04.

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1. INTRODUCTION

Automotive materials engineering is no longer governed by mass reduction alone. Vehicle designers must simultaneously manage safety, manufacturability, reparability, circularity, and reduced dependence on fossil carbon. Polymer composites remain attractive because they offer high specific stiffness, corrosion resistance, vibration damping, part integration, and broad geometric freedom. Industry data indicate that plastics and polymer composites account for a meaningful and growing share of vehicle mass, while lightweight substitution remains linked to fuel and energy efficiency ([Creates & Competes, n.d.](#)).

Conventional automotive composites commonly use petroleum-derived epoxy, unsaturated polyester, vinyl ester, polypropylene, polyamide, and polyurethane matrices. These materials are technically mature, but their fossil feedstocks, hazardous precursors, crosslinked networks, and difficult fiber-matrix separation create environmental and end-of-life challenges. European vehicle-circularity policy also places increasing emphasis on recycled content, dismantlability, material documentation, reuse, and improved end-of-life treatment ([Proposal, 2023](#)). Resin selection must therefore combine performance, processing, environmental, and supply considerations.

Bio-based matrices derive all or part of their carbon from renewable feedstocks such as vegetable oils, cardanol, lignin, vanillin, furan compounds, itaconic acid, sugars, starch derivatives, and castor-oil-based monomers. Thermosetting options include bio-epoxy, furan epoxy, bio-unsaturated polyester, and dynamic covalent networks; thermoplastic options include PLA, PBS, PHA, bio-PE, and bio-polyamides such as PA11. These matrices can be reinforced with flax, hemp, kenaf, jute, wood fibers, or hybrid mineral fibers.

Renewable origin is not a performance guarantee. Flexible aliphatic structures can reduce glass-transition temperature, natural fibers can increase water uptake, and fire performance may remain inadequate. Conversely, partially bio-based aromatic systems can provide higher stiffness and thermal resistance than highly renewable but weakly crosslinked formulations. The relevant design question is therefore whether a material-process-component system satisfies a defined service envelope.

The research gap is the lack of a concise and traceable engineering map that converts heterogeneous bio-resin evidence into component-level automotive decisions. This study addresses the gap by displaying representative property anchors before scoring, defining a reproducible 0-10 rubric, stating the basis of the weights, testing rank stability, and mapping candidate routes to automotive component classes and minimum validation needs.

2. LITERATURE REVIEW**2.1. Bio-based thermosetting matrices**

Bio-epoxy is the most direct thermoset substitution route because epoxy chemistry is already established for infusion, resin-transfer molding, prepregging, adhesive bonding, and semi-structural laminates. Renewable precursors include vegetable oils, cardanol, lignin, vanillin, eugenol, and furan compounds. Their properties are structure-dependent: flexible aliphatic segments can improve toughness and damping but reduce thermal margin, while aromatic structures generally increase stiffness and glass-transition temperature at the cost of viscosity and processing complexity ([Liu et al., 2021](#)).

Aromatic lignin- and vanillin-derived systems show the clearest route toward high-performance bio-epoxy. Lignin fraction and molecular structure strongly affect network properties ([Gioia et al., 2020](#); [Xue et al., 2023](#)), while divanillin and vanillin-derived systems have demonstrated recyclable, flame-retardant, or high-stiffness behavior ([Fang et al., 2020](#); [Ma et al., 2022](#); [Memon et al., 2020](#); [Su et al., 2020](#); [Zhi et al., 2023](#); [Zhou et al., 2024](#)). A recent DGEVA-DDS formulation reported 70% bio-based content, a DMA T_g of 140 degrees C, bending stiffness of 3.84 GPa, and fracture toughness of 1.33 MPa m^{0.5}, illustrating the performance potential of aromatic renewable chemistry ([Kaushik et al., 2025](#)).

Vegetable-oil and cardanol systems offer accessible feedstocks and low initial viscosity but often require aromatic comonomers, post-curing, fillers, or hybrid skins to improve heat resistance. Furan-derived thermosets offer another high-renewable route; however, stoichiometry, catalyst selection, and cure schedule strongly influence final network structure and processing reliability ([Faggio et al., 2023](#); [Louisy et al., 2022](#); [Marotta et al., 2022](#); [Zaidi et al., 2024](#)).

2.2. Bio-based thermoplastic matrices

Thermoplastics provide a different circularity pathway because they can be reheated, welded, reshaped, and mechanically recycled. PLA, PBS, and PHA are attractive for interior trim, liners, and low-load housings

because they are commercially available and compatible with injection molding, compression molding, thermoforming, film stacking, and additive manufacturing. Their limitations include low heat-deflection temperature, creep, hydrolysis, impact brittleness, and moisture sensitivity when combined with hydrophilic fibers (Ilyas et al., 2022; Sriseubsai & Praemettha, 2024).

Manufacturing studies demonstrate that natural-fiber/PLA systems can achieve useful structural efficiency when fiber alignment and consolidation are controlled. In hot-pressed quasi-unidirectional composites, flax/PLA reached a tensile modulus of 12.14 GPa and tensile strength of 95 MPa, while flexural modulus and strength reached 9.87 GPa and 147.13 MPa, respectively (Möhl et al., 2022). These values support interior and secondary structural use, but the absence of harmonized moisture and high-temperature data limits direct component qualification.

Bio-based engineering thermoplastics provide a higher durability and temperature margin. PA11, derived from castor-oil chemistry, combines chemical resistance, toughness, and established melt processing. Alkaline modification of beech fibers increased their thermal stability and improved the elastic and storage modulus of PA11 composites, supporting technical applications while emphasizing the need for fiber drying and interface control (Zierdt et al., 2015).

2.3. Natural-fiber interfaces and property evidence

Natural fibers reduce density and may improve acoustic damping, but hydrophilic cellulose and hemicellulose create a weak interface with many polymer matrices. Alkali treatment, silane coupling, acetylation, maleated compatibilizers, and barrier coatings can improve wetting and dimensional stability. Nevertheless, water absorption remains formulation- and conditioning-dependent, and dry coupon data should not be treated as proof of hot-wet durability (Elfaleh et al., 2023; Mohammed et al., 2023; Patel et al., 2023). Table 1 presents the representative quantitative and qualitative anchors used to constrain the scoring model.

Table 1. Representative evidence anchors used to constrain the route-level scoring.

Route / example	Reported mechanical evidence	Thermal / moisture evidence	Engineering interpretation	Source
DGEVA-DDS aromatic vanillin epoxy	Bending stiffness 3.84 +/- 0.02 GPa; fracture toughness 1.33 +/- 0.23 MPa m ^{0.5}	DMA Tg 140 degrees C; 70% bio-based content	High-performance matrix; minor process adjustment reported	(Kaushik et al., 2025)
Flax/PLA quasi-UD composite	Tensile: 95 MPa, 12.14 GPa; flexural: 147.13 MPa, 9.87 GPa	Moisture and elevated-temperature retention not reported	Hot-pressed textile semi-finished route; strong directional properties	(Möhl et al., 2022)
Cotton/PLA quasi-UD composite	Tensile: 81.22 MPa, 9.95 GPa; flexural: 104.7 MPa, 6.79 GPa	Moisture and elevated-temperature retention not reported	Hot pressing; more ductile response than flax variant	(Möhl et al., 2022)
PA11/alkali-treated beech fiber	Elastic and storage modulus increased after fiber treatment	Fiber TGA onset increased from 290 to 330 degrees C; water uptake not quantified	Melt-processed technical composite; drying and interface control required	(Zierdt et al., 2015)
Furan/maleic-anhydride epoxy	Higher ultimate strain but slightly lower modulus and strength than comparison systems	Tg lower than comparison systems; exact route remains cure-dependent	Fully bio-based adhesive route with high curing reactivity	(Faggio et al., 2023)
Natural-fiber polymer composites	Property loss varies with fiber, loading, treatment, and conditioning	Water uptake causes swelling and interface degradation	Hot-wet validation and barrier treatment required	(Mohammed et al., 2023)

3. RESEARCH METHOD

3.1. Evidence-base audit and inclusion rules

This study is a structured integrative engineering review, not an exhaustive systematic review or a machine-learning study. During revision, the bibliography was audited for topical relevance and traceability. Weakly related sources on engine biofuels, food packaging, and generic machine-learning reviews were removed. The final auditable corpus contains 23 sources: 22 peer-reviewed technical studies or reviews

directly addressing bio-based matrices, natural-fiber composites, processing, durability, or automotive-relevant performance, and four policy or industry sources used only for introductory context.

Technical sources were retained when they identified the matrix chemistry, reported mechanical, thermal, moisture, processing, circularity, or application information, and provided sufficient detail for engineering interpretation. Sources were excluded from scoring when the matrix identity was unclear, the application context was unrelated, or sustainability claims were not connected to function or processing. Titles, abstracts, DOI records, and source roles were checked against the reference list. Because the original database export and historical hit counts were unavailable, unsupported PRISMA-stage counts were removed and no claim of exhaustive coverage is made. Figure 1 therefore reports evidence accounting rather than a PRISMA selection process.

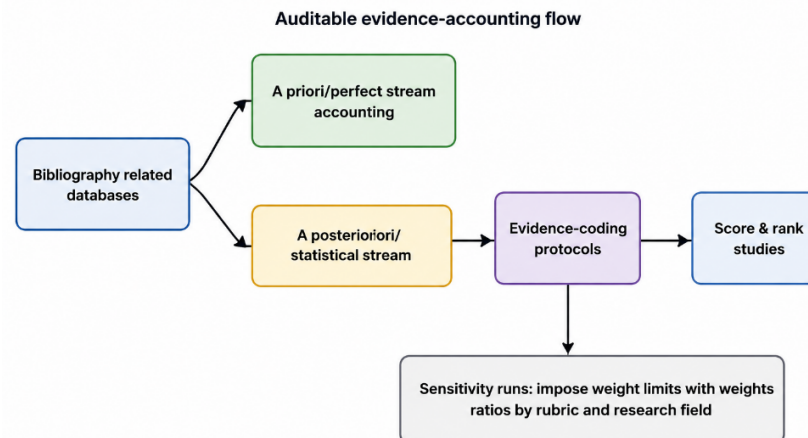


Figure 1. Auditable evidence-accounting flow for the revised integrative engineering review.

3.2. Data extraction and route definition

The extracted fields were feedstock, matrix family, reinforcement, processing route, density, strength or modulus, Tg or heat-deflection behavior, water uptake or hot-wet retention, cure or melt behavior, renewable-carbon evidence, recycling route, automotive relevance, and source. Numerical results were retained with their original test context. Missing information was recorded as not reported and did not receive an assumed favorable score. Table 1 provides the main quantitative anchors, while review evidence was used to interpret broader property and maturity ranges.

Five route families were assessed: partly bio-based cardanol/oil epoxy, aromatic lignin/vanillin bio-epoxy, furan/itaconic thermosets, PLA/PBS/PHA thermoplastics, and bio-based engineering thermoplastics represented by PA11 and bio-PE. The route-level approach avoids treating a single laboratory formulation as representative of an entire automotive material grade.

3.3. Scoring rubric and criterion weights

Each route was scored from 0 to 10 for eight criteria. The rubric in Table 2 defines the evidence bands. Scores of 0-3 indicate weak or laboratory-only evidence, 4-6 indicate moderate suitability with substantial controls, 7-8 indicate credible engineering readiness, and 9-10 require strong performance or industrial validation. Route scores were assigned by author consensus after comparing the sources listed in Table 1 and the broader evidence discussed in Section 2.

The weights were author-assigned from an automotive mechanical-design perspective rather than derived from an expert survey or AHP pairwise comparison. Mechanical capability (0.18) and thermal window (0.15) received the largest weights because load transfer and dimensional stability are fundamental screening constraints. Specific stiffness and process readiness each received 0.13; moisture durability and bio-carbon benefit each received 0.12; circularity received 0.10; and supply maturity received 0.07. The explicit disclosure of author assignment is important because the ranking remains an early-screening tool rather than a universal preference model.

Table 2. Explicit scoring rubric for the eight engineering criteria.

Criterion	Low (0-3)	Moderate (4-6)	High (7-8)	Exceptional (9-10)
Mechanical capability	Weak coupon evidence or brittle/interface failure	Moderate non-structural performance	Repeatable good performance and semi-structural potential	Automotive benchmark plus fatigue/impact evidence
Specific stiffness	No credible mass-saving case	Comparable only with thickness increase	Credible E/rho and gauge reduction	Component-level mass reduction demonstrated
Thermal window	Tg/HDT below about 50 degrees C	About 50-90 degrees C; controlled interior use	About 90-120 degrees C; demanding cabin/exterior use	Above 120 degrees C or validated under-hood/paint cycle
Moisture durability	High uptake and major property loss	Moderate uptake; treatment needed	Good retained dimensions and properties	Long-term hot-wet/weathering validation
Process readiness	Chemistry concept or unstable coupons	Repeatable lab/pilot route with cycle limits	Compatible with established molding equipment	Automotive-scale controlled cycle and quality system
Bio-carbon benefit	Negligible or unverified renewable carbon	Moderate formulation-dependent benefit	High renewable content with evidence	Very high verified content and life-cycle benefit
Circularity potential	No credible recovery route	Downcycling or difficult separation	Reprocessing, chemical recycling, or disassembly demonstrated	Closed-loop/high-value recycling at relevant scale
Supply maturity	Research synthesis only	Commercial but limited grades/suppliers	Established grades and specifications	Automotive-qualified scalable supply base

Table 3. Author-assigned criterion weights and engineering rationale.

Criterion	Weight	Automotive-design rationale
Mechanical capability	0.18	Load transfer, stress concentration, vibration
Specific stiffness	0.13	Mass reduction at required dimensional stiffness
Thermal window	0.15	Cabin, exterior, paint-shop, and under-hood exposure
Moisture durability	0.12	Long-term dimensional and property retention
Process readiness	0.13	Scale-up beyond laboratory coupons
Bio-carbon benefit	0.12	Renewable-carbon value beyond performance
Circularity potential	0.10	End-of-life vehicle compatibility
Supply maturity	0.07	Cost, consistency, grades, and supplier base

3.4. Weighted score and sensitivity analysis

The weighted score for route i was calculated as $S_i = \sum(w_j x_{ij})$, where w_j is the normalized weight and x_{ij} is the 0-10 route score. Weight uncertainty was tested through 100,000 Monte Carlo iterations using a fixed random seed. In each iteration, every base weight was independently multiplied by a uniform factor between 0.80 and 1.20 and then renormalized to sum to 1.00. The median and 5th-95th percentile intervals were calculated for each route, together with the proportion of simulations in which each route ranked first. This analysis evaluates uncertainty in the weights; it does not yet propagate uncertainty in the underlying criterion scores.

4. RESULTS AND DISCUSSION

4.1. Engineering relevance of the resin families

The evidence confirms that renewable content alone is an insufficient selection rule. Aromatic bio-epoxy provides the strongest thermoset combination of stiffness and temperature resistance, but its viscosity control, cure standardization, and supplier maturity remain lower than those of conventional systems.

Furan/itaconic routes offer high renewable content and attractive thermal chemistry, but automotive process history is limited. PLA/PBS/PHA systems offer mature short-cycle thermoplastic processing and high circularity, yet heat and moisture remain constraints. Bio-based engineering thermoplastics provide the most balanced combination of process readiness, moisture resistance, thermal margin, and end-of-life potential.

The property evidence also shows why route-level screening must remain conservative. (Kaushik et al., 2025) demonstrate high-performance vanillin epoxy under a specific aromatic curing system, whereas (Möhl et al., 2022) demonstrate high directional stiffness in well-aligned PLA/flax composites. Neither result can be transferred directly to a different fiber architecture, cure schedule, conditioning state, or component geometry. The scores therefore represent engineering evidence bands, not design allowables.

4.2. Multi-criteria ranking and robustness

Table 4A. Performance and durability scores for the candidate matrix routes.

Matrix route	Mechanical	E/rho	Thermal	Moisture
Partly bio-epoxy (cardanol/oil)	7.0	6.5	6.2	6.0
Aromatic bio-epoxy (lignin/vanillin)	8.5	7.8	8.6	6.5
Furan/itaconic thermoset	7.4	7.2	7.8	6.3
PLA/PBS/PHA thermoplastic	5.5	6.0	4.8	4.6
Bio-based engineering thermoplastic	7.5	7.0	7.6	7.2

Table 4B. Manufacturing, sustainability, maturity, and weighted scores.

Matrix route	Process	Bio-C	Circularity	Supply	Weighted
Partly bio-epoxy (cardanol/oil)	8.0	7.0	4.2	7.2	6.56
Aromatic bio-epoxy (lignin/vanillin)	5.6	8.5	5.3	4.8	7.23
Furan/itaconic thermoset	5.5	8.2	5.8	4.6	6.80
PLA/PBS/PHA thermoplastic	8.5	9.0	8.0	7.2	6.53
Bio-based engineering thermoplastic	9.0	6.5	8.2	7.5	7.56

The base ranking places bio-based engineering thermoplastics first at 7.56, aromatic bio-epoxy second at 7.23, furan/itaconic thermosets third at 6.80, partly bio-based epoxy fourth at 6.56, and PLA/PBS/PHA thermoplastics fifth at 6.53. The heatmap in Figure 2 clarifies the trade-offs hidden by a single score. Bio-based engineering thermoplastics lead in process readiness, circularity, moisture durability, and supply maturity. Aromatic bio-epoxy leads in mechanical and thermal capability but is penalized by lower process and supply maturity. PLA/PBS/PHA scores strongly in renewable carbon, circularity, and processing but has the weakest thermal and moisture profile.

The sensitivity analysis supports the stability of the first-place result. Bio-based engineering thermoplastics remained first in all 100,000 simulations, with a 5th-95th percentile score interval of 7.51-7.61. Aromatic bio-epoxy remained centered at 7.23 with an interval of 7.13-7.32. The close base scores of partly bio-based epoxy and PLA/PBS/PHA should not be interpreted as a meaningful universal ordering because component requirements can easily reverse their preference. Figure 3 therefore reports sensitivity intervals rather than unsupported statistical confidence bars.

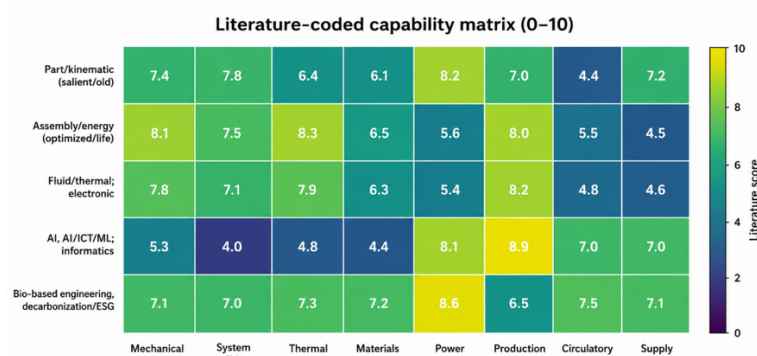


Figure 2. Literature-coded capability matrix for the five candidate routes.

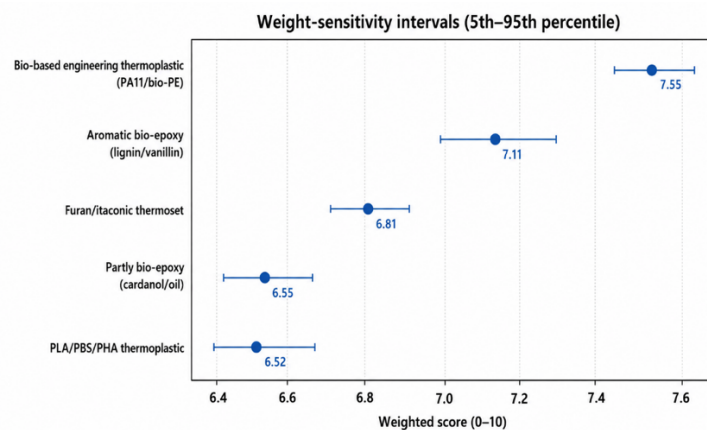


Figure 3. Sensitivity intervals for the weighted route ranking under $\pm 20\%$ weight variation.

4.3. Automotive component suitability

The component map in Table 6 converts route-level evidence into practical design guidance. Door trim, headliners, parcel shelves, and trunk liners prioritize low mass, acoustic damping, recyclability, surface feel, and moderate mechanical loads. PLA/PBS/PHA and bio-based engineering thermoplastics are credible when moisture and dimensional stability are controlled. Seat backs and interior brackets require better creep, fatigue, insert retention, and joint integrity, favoring PA11-type thermoplastics or aromatic bio-epoxy hybrids. Exterior and under-hood covers require stronger thermal, weathering, and coating performance.

Battery-enclosure covers and crash-relevant parts require a more conservative threshold. Renewable content cannot substitute for flame, smoke, toxicity, dielectric, impact, fatigue, and thermal-runaway-adjacent validation. Hybrid glass or basalt reinforcement may be technically appropriate, but it should be treated as a component architecture rather than a separate matrix family and evaluated for disassembly and recycling consequences.

Table 5. Component-level interpretation of the route screening results

Component class	Primary requirement	Preferred route	Minimum design control
Door trim/headliner	Low mass, acoustic damping, appearance, low odor	PLA/PBS/PHA or bio-based engineering thermoplastic	Coupling agents, emissions, moisture and dimensional stability
Trunk liner/parcel shelf	Stiffness, impact tolerance, recyclability, cost	PLA/PBS with flax/kenaf or PA11-type route	Compression molding or thermoforming; check water exposure
Seat back/interior bracket	Specific stiffness, creep, fatigue, joint integrity	PA11-type thermoplastic or aromatic bio-epoxy	Insert design, screw retention, creep and fatigue
Exterior panel	Surface quality, UV/water aging, thermal cycling	Aromatic bio-epoxy or protected thermoplastic	Coating, hot-wet aging and paint-cycle screening
Under-hood acoustic cover	Heat, oil mist, vibration, insulation	Engineering thermoplastic or aromatic epoxy with filler	Drying, heat aging, oil exposure and flame behavior
Battery enclosure cover	Fire/smoke, thermal barrier, electrical safety	Flame-retarded engineering thermoplastic or hybrid bio-epoxy	Flame, smoke, dielectric and thermal-runaway-adjacent tests

4.4. Technical risks and validation priorities

Moisture uptake is the most persistent natural-fiber risk because swelling and interface degradation reduce stiffness and dimensional accuracy. Low T_g is especially important for flexible vegetable-oil and cardanol systems. Fire and smoke behavior requires independent testing because both organic matrices and natural fibers contribute fuel. Cure time affects takt-time compatibility for thermosets, while agricultural variability affects incoming quality control. End-of-life separation remains difficult for crosslinked networks and mixed reinforcements. The risk register in Table 7 links each barrier to a mitigation route and minimum validation requirement.

The practical implication is a staged qualification strategy. Early screening should eliminate routes that cannot meet service temperature or moisture requirements. The remaining candidates should be compared

at equal component function, followed by hot-wet aging, creep, fatigue, fire behavior, joining, and component-scale impact tests. Life-cycle analysis should use service life and retained performance as functional units rather than mass alone.

Table 6. Technical risk register for bio-based automotive composite matrices.

Technical barrier	Failure mechanism	Mitigation and minimum validation
Moisture uptake	Fiber swelling and interface damage	Silane/alkali treatment, compatibilizer, coating; water absorption and hot-wet aging
Low Tg / heat deflection	Softening near service temperature	Aromatic monomers, post-cure, fillers; DMA/DSC, HDT and creep
Fire and smoke	Higher heat release and smoke from organic phases	Phosphorus systems, mineral fillers, glass/basalt skins; UL-94, cone calorimetry and smoke density
Fiber variability	Changes in strength, diameter, moisture, and porosity	Supplier grading, incoming QC and statistical knock-down factors
Long thermoset cure	Poor takt-time and increased process energy	Fast hardeners, heated compression, prepreg/SMC; rheology and cure map
End-of-life separation	Crosslinked networks and mixed fibers limit recovery	Thermoplastics, cleavable networks, design for disassembly; recycling trials and LCA sensitivity

5. CONCLUSION

No bio-based resin route dominates all eight engineering criteria. Bio-based engineering thermoplastics achieved the highest base score of 7.56, followed by aromatic lignin/vanillin bio-epoxy at 7.23 and furan/itaconic thermosets at 6.80. Under independent $\pm 20\%$ variation of all weights, the leading route remained first in every simulation and produced a 5th-95th percentile interval of 7.51-7.61.

For automotive implementation, the results support a component-specific strategy. Thermoplastic routes are attractive for recyclable interior panels, trunk liners, seat backs, and selected under-hood covers, whereas aromatic bio-epoxy is more appropriate when higher stiffness, bonding performance, or temperature resistance is required. Battery-adjacent and crash-relevant parts remain conditional on dedicated fire, smoke, dielectric, fatigue, impact, and component-scale validation.

The ranking is an early-screening result rather than final qualification because the literature is heterogeneous and the model contains engineering judgment. Future work should harmonize property extraction, quantify uncertainty in both scores and weights, perform function-normalized life-cycle and finite-element studies, and validate the most promising routes using consistent coupon and component tests.

AUTHOR CONTRIBUTIONS

Teuku Marjuni: conceptualization, literature synthesis, and original draft. Fauzi Ibrahim: methodology, decision model, sensitivity analysis, review, and editing.

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