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Biochar as reinforcement for composite materials in the automotive industry

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ABSTRACT

Biochar, also referred to as biocarbon when positioned as an engineering filler, is a carbon-rich solid obtained by thermochemical conversion of renewable biomass and organic waste under oxygen-limited conditions. Its low density, tunable surface chemistry, porous morphology, thermal stability and potential carbon-storage value make it a promising reinforcement for polymer composites in the automotive industry. This article reviews the use of biochar as a reinforcing phase in polypropylene, polylactic acid, polyamide, epoxy and rubber composite systems from an engineering design perspective. The review focuses on the interaction between feedstock, pyrolysis temperature, ash and carbon content, particle-size distribution, interfacial bonding, melt-processing behavior and automotive qualification requirements. Literature evidence shows that biochar can increase tensile and flexural stiffness, improve heat-deflection resistance, reduce smoke and heat release, and provide a mass advantage compared with mineral fillers. However, strength and impact performance are strongly non-monotonic and can degrade when agglomeration, high viscosity, weak wetting or excessive ash content dominate the microstructure. A proposed Automotive Biochar Composite Readiness Index is introduced to compare matrix-specific readiness for interior trim, instrument-panel carriers, under-hood covers, battery-enclosure inserts, rubber compounds and additive-manufactured fixtures. The analysis indicates that near-term implementation is strongest for semi-structural and non-structural parts, whereas crash-critical structures require hybridization, robust CAE material cards and full ageing, fire, fogging, odor and life-cycle assessment. The paper concludes with a qualification roadmap and design rules for translating laboratory biochar composites into automotive-grade materials.

Keywords: *biochar, biocarbon, polymer composites, automotive lightweighting, polypropylene, polyamide, polylactic acid, flame retardancy, circular economy, material qualification.*

1. INTRODUCTION

Automotive materials are increasingly evaluated using a combined mechanical, manufacturing and environmental lens. Conventional vehicle lightweighting was historically driven by mass reduction, stiffness-to-weight ratio and fuel economy; current engineering practice also requires transparent life-cycle carbon accounting, recyclability, durability and compliance with safety regulations. A recent vehicle-lightweighting review emphasizes that mass reduction reduces tractive energy demand and can generate system-level benefits, but its carbon benefit must be assessed across material production, manufacturing, vehicle use and end-of-life stages (Wang et al., 2026).

Polymer composites occupy an important position in this transition because they combine low density, shape complexity, corrosion resistance and part consolidation. In automotive interiors, exterior panels, under-hood covers, acoustic packages and selected structural carriers, mineral fillers, glass fibers, carbon black and short carbon fibers are widely used. These fillers provide stiffness, dimensional stability and sometimes conductivity or flame resistance, but they can increase density,

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embodied energy, tool wear and end-of-life complexity. Natural fibers and nanocellulosic reinforcements have therefore attracted interest as low-density alternatives for automotive polymer composites (Ferreira et al., 2019; Capretti et al., 2024; Ullah et al., 2025).

Biochar expands this biocomposite strategy from fibrous reinforcement to a carbonaceous particulate reinforcement. The term biochar is commonly used for biomass-derived carbon obtained by pyrolysis, while biocarbon is often used when the material is engineered for composite, energy or environmental applications. Biocarbon materials are produced from renewable feedstocks at temperatures typically above 350 deg C under limited oxygen, and their structure, surface chemistry, porosity and ash content are highly dependent on feedstock and thermal history (Mohanty et al., 2024). In composites, biochar can act through mechanical interlocking, crack deflection, nucleation, thermal shielding and char-barrier formation (Das et al., 2021; Aboughaly et al., 2023).

The automotive opportunity is attractive because biochar can potentially combine five functions: reinforcement, density reduction, heat resistance, flame/smoke suppression and circular carbon utilization. Nevertheless, biochar is not a drop-in replacement for all conventional fillers. Reported properties differ substantially among polypropylene, PLA, PA6, epoxy and rubber matrices, and performance is sensitive to particle size, surface area, moisture, ash content, coupling chemistry and processing route (Das et al., 2021; Aboughaly et al., 2023; Das et al., 2015; Das et al., 2016; Ikram et al., 2016; Das et al., 2017; Anerao et al., 2023; Zouari et al., 2022; Brdlik et al., 2024; Minugu et al., 2021; Venkata Suresh et al., 2026; Ghosh et al., 2026; Karunanayake et al., 2025). A rigorous engineering review is therefore needed to translate scattered laboratory evidence into component-level design windows.

This article provides such a review. The objective is not to claim that biochar is universally superior to mineral or synthetic carbon fillers, but to identify where biochar is technically credible, where it requires hybridization, and what tests are needed before adoption in automotive components. The original contribution of this manuscript is a property-process-sustainability framework and a proposed Automotive Biochar Composite Readiness Index for matrix-specific application screening.

2. RESEARCH METHOD

A scoping review approach was used to synthesize peer-reviewed studies on biochar and biocarbon filled polymer composites. The review emphasized publications reporting at least one measurable engineering property relevant to automotive applications, including tensile strength, tensile modulus, flexural strength, flexural modulus, impact toughness, heat resistance, dimensional stability, flame retardancy, smoke production, rheology, density, ageing or life-cycle implications.

The scope intentionally covers thermoplastics and thermosets that are relevant to automotive manufacturing: PP and wood/PP composites for interior trim and semi-structural parts; PLA for bio-based components and additive manufacturing; PA6 for under-hood and interior engineering plastics; epoxy for coatings, inserts and structural composite sub-systems; and rubber compounds where biochar is considered as a partial carbon-black alternative. Standards and qualification requirements are discussed at a generic level because individual vehicle manufacturers apply internal specifications in addition to ASTM, ISO, UL and FMVSS-derived requirements.

Table 1. Literature Screening Logic and Engineering Interpretation

Item	Implementation in this review	Reason for automotive relevance
Core keywords	biochar, biocarbon, polymer composite, polypropylene, PLA, polyamide, epoxy, rubber, automotive, flame retardancy, mechanical properties	Captures both material-science and component-application literature.
Primary period	2015-2026, with emphasis on recent 2021-2026 work	Biochar composite research has expanded rapidly in the last decade.
Inclusion focus	Studies with measured mechanical, thermal, flame, ageing, density or processing data	Allows conversion of qualitative claims into design implications.
Exclusion focus	Soil-only biochar studies, adsorption-only studies and papers without polymer composite relevance	Avoids diluting automotive material conclusions.
Synthesis method	Narrative engineering synthesis supported by comparative tables, color figures and a proposed readiness index	A meta-analysis is not appropriate because matrices, fillers, tests and processing routes vary widely.

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Item	Implementation in this review	Reason for automotive relevance
Data handling	Numerical values are reported only when directly available in cited sources; design maps are labelled as engineering synthesis	Maintains traceability and avoids treating conceptual trends as experimental data.

3. RESULTS AND DISCUSSION

3.1 Biochar as a Reinforcement Phase

The reinforcement potential of biochar originates from its hierarchical carbon structure. During pyrolysis, lignocellulosic precursors undergo dehydration, depolymerization, aromatization and partial graphitic ordering. The resulting particles usually contain aromatic carbon domains, oxygen-containing surface groups, pores, mineral ash and residual functional groups. The balance among these features controls polymer wetting, interfacial friction, stress transfer, electrical conductivity and thermal stability (Mohanty et al., 2024; Das et al., 2021; Aboughaly et al., 2023).

A central engineering advantage is the combination of low density and thermal stability. The PA6 biocarbon study by Ghosh, Mohanty and Misra reported that waste-derived biocarbons can be used at 20-30 wt.% loadings, improve tensile and flexural modulus, increase heat-deflection temperature and yield composites about 10% lighter than selected talc and glass-fiber systems (Ghosh et al., 2026). For PP systems, biochar has repeatedly shown improvements in stiffness and fire behavior when the morphology and coupling strategy are controlled (Das et al., 2015; Das et al., 2016; Ikram et al., 2016; Das et al., 2017).

The central engineering risk is heterogeneity. Biochar from rice husk, wood, wheat straw, corncob, nutshells, sludge and plastic-paper waste differs in fixed carbon, ash, silica, alkaline metals, pore volume and polarity. These differences can be beneficial or harmful. High surface area can promote mechanical interlocking, but it can also increase melt viscosity or trap flame retardants. Fine particles can strengthen and toughen a matrix, but excessive fines can agglomerate. High ash can improve char yield or flame resistance, but it can introduce defects, moisture sensitivity and inconsistent color.

Table 2. Biochar Attributes and Expected Engineering Influence In Automotive Polymer Composites.

Biochar attribute	Typical origin or control parameter	Positive influence	Potential failure mode	Recommended verification
Carbon content and aromaticity	Higher pyrolysis temperature, lignin-rich feedstock	Thermal stability, char-barrier formation, possible conductivity	Brittleness and reduced surface polarity at very high carbonization	CHNS, Raman/XRD, TGA, electrical resistivity
Ash and mineral content	Rice husk, agricultural residues, sludge, mixed waste	Stiffness, char yield, possible flame resistance	Abrasive particles, moisture sensitivity, batch variability	Ash analysis, ICP-OES, moisture uptake, tool-wear check
Specific surface area	Activation, porosity, milling	Mechanical interlocking and polymer infiltration	High viscosity, trapped additives, poor impregnation at high loading	BET, rheology, SEM fracture surface
Particle-size distribution	Grinding, sieving, ball milling, wet milling	Fine particles improve dispersion and surface area	Agglomeration, nozzle clogging in FDM, stress concentrators	Laser diffraction, SEM, micro-CT, filtration/nozzle tests
Surface functionality	Feedstock oxygen, low-temperature char, oxidation/plasma treatment	Improved wetting and interfacial adhesion	Thermal instability, moisture adsorption	FTIR, XPS, contact angle, dynamic mechanical analysis
Bulk density and morphology	Feedstock cellular structure and compaction	Lightweighting and acoustic damping potential	Poor feeding, dusting, occupational exposure	Tapped density, dust control, feeding trials

3.2 Automotive Composite Requirements

Automotive qualification is more demanding than coupon-level strength improvement. A material used in an interior panel must meet appearance, odor, fogging, scratch, ultraviolet ageing, flammability and dimensional stability requirements. An under-hood cover must survive heat cycling, oil exposure, vibration and flame/smoke constraints. A load-bearing carrier requires reliable stiffness, impact performance, creep resistance, fatigue data and CAE material cards. A battery-related component introduces thermal runaway and electrical-insulation constraints.

Biochar composites therefore should be evaluated as multi-functional materials rather than single-property fillers. The same biochar that

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improves modulus may reduce impact toughness. The same high-surface-area biochar that promotes interlocking may create processing difficulties. The same carbon-rich filler that improves char formation may alter conductivity, color or electromagnetic behavior. These trade-offs require application-specific screening.

Table 3. Automotive Component Classes and Material Requirements for Biochar Composites.

Component class	Candidate matrix/filler system	Critical requirements	Biochar opportunity	Key qualification gate
Interior trim, console, pillar covers	PP/biochar, PP/wood/biochar, PLA/biochar blends	Low VOC, odor, fogging, scratch, color, flame, impact	Low density, stiffness, black coloration, recycled-content story	FMVSS/UL flammability, odor/fogging, UV ageing, impact at low temperature
Door panels and instrument-panel carriers	PP/WPC/biochar, PA6/biocarbon hybrids	Stiffness, dimensional stability, clip retention, heat ageing	Stiffness and reduced pHRR, possible acoustic damping	D638/D790/D256, CLTE, heat ageing, clip pull-out
Under-hood covers and ducts	PA6/biocarbon, PA6/talc/biocarbon hybrids	HDT, oil exposure, vibration, creep, flame/smoke	Thermal stability and mass reduction versus mineral fillers	HDT, thermal cycling, fluid resistance, cone calorimetry
Battery-enclosure inserts and thermal barriers	PA6/biocarbon, epoxy/biochar coatings, hybrid FR systems	Thermal insulation, flame, smoke, electrical insulation, dimensional stability	Char formation and thermal shielding	UL-94, cone calorimeter, dielectric properties, abuse testing
Rubber seals, tires and damping parts	Natural rubber or synthetic rubber with partial biochar replacement for carbon black	Dynamic fatigue, abrasion, hysteresis, ageing, oil/ozone resistance	Carbon-black substitution, sustainability, damping control	DIN abrasion, DMA hysteresis, fatigue crack growth, ageing
3D-printed jigs, fixtures and low-volume parts	PLA/biochar FDM filament	Printability, stiffness, dimensional stability, surface finish	Stiffness, bio-based content, rapid prototyping	Nozzle clogging, layer adhesion, tensile and impact coupons

3.3 Evidence Map from Polymer Systems Relevant to Automotive Engineering

The reviewed studies show that biochar reinforcement is most consistent when the performance target is stiffness, heat resistance or char formation. Stiffness gains are expected because rigid carbonaceous particles restrict polymer-chain mobility and increase load-bearing solid volume fraction. In contrast, tensile strength and impact toughness require interfacial adhesion, particle dispersion and crack-tip control; they are therefore more sensitive to loading level and surface treatment. Figure 1 compiles selected quantitative improvements from the reviewed literature. The strongest reported single-property gains include tensile and flexural improvements in selected epoxy systems, impact-toughness gains in impact-modified PLA/biochar composites and modulus gains in PA6/biocarbon composites. The chart should be interpreted as an evidence map rather than a direct ranking because different matrices, feedstocks, test standards and processing routes were used.

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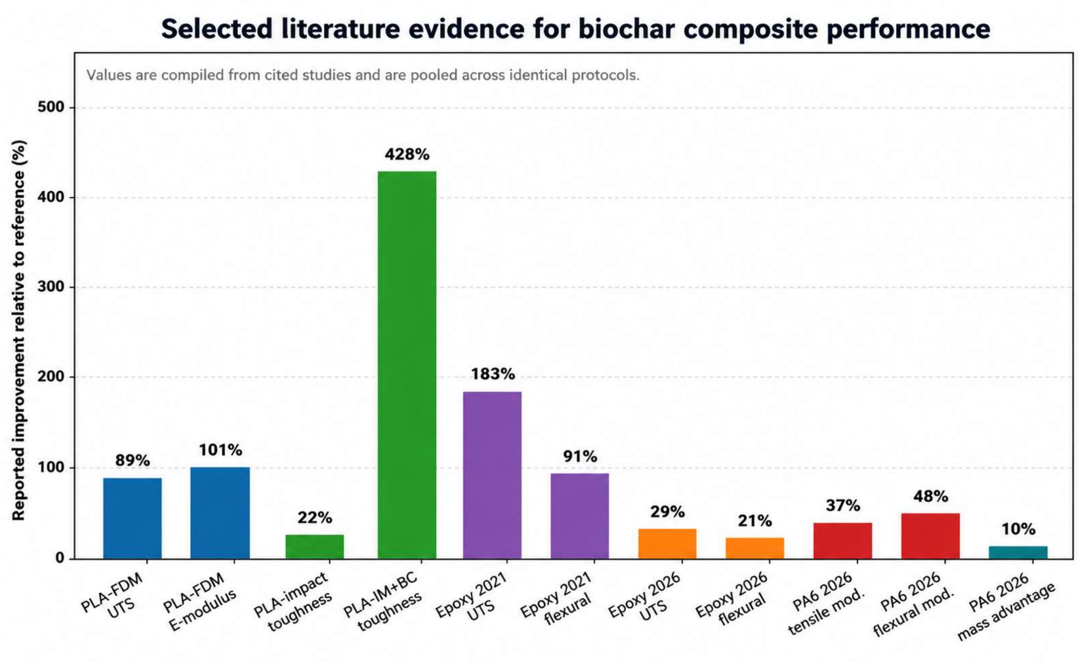

Figure 1. Selected Literature Evidence for Biochar Composite Performance. Values Are Reported Relative to Each Study Reference Material and Should Not Be Cross-Normalized Without Identical Protocols

Table 4. Evidence matrix for biochar-reinforced composite systems with automotive relevance.

Matrix or system	Biochar level and source context	Processing route	Reported technical outcome	Engineering limitation	Automotive interpretation	Refs.
Wood/PP composite with biochar	6-30 wt.% biochar, with wood/PP formulation context	Composite compounding and molded coupon testing	At 24 wt.% biochar, tensile/flexural strength and moduli improved; 12 wt.% showed ductile behavior; 18 wt.% showed strong thermal stability	Optimal loading is formulation-specific and depends on wood content and coupling	Suitable for interior trim and semi-structural panels where stiffness and dimensional stability are prioritized	(Das et al., 2015)
Biochar/PP biocomposite	15-35 wt.% biochar	Thermoplastic compounding and mechanical/flame characterization	Tensile modulus, flexural strength and flexural modulus improved; peak heat release and smoke production reduced	High filler can reduce ductility and introduce processing sensitivity	Promising for black interior parts, housings and covers where flame/smoke reduction is valuable	(Das et al., 2016)
Parametric PP/biochar system	Activated biochar with high surface area; MAPP and wood content varied	Parametric compounding study	Coupling and wood/biochar ratio strongly controlled mechanical and flammability response	Biochar alone is not sufficient; interface chemistry is a design variable	Use MAPP or compatible functionalization when targeting load transfer in PP	(Ikram et al., 2016)
PP/biochar fire-performance balance	Biochar combined with flame-retardant strategy	Thermoplastic composite formulation	Higher biochar fraction improved flame performance; excessive pore volume could trap flame retardants and reduce mechanical efficiency	Fire-performance and mechanical-property optima may not coincide	Optimize filler porosity and FR package together rather than independently	(Das et al., 2017)

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Matrix or system	Biochar level and source context	Processing route	Reported technical outcome	Engineering limitation	Automotive interpretation	Refs.
PLA/biochar FDM filament	5 wt.% biochar in PLA for FDM	Filament extrusion and FDM printing	Ultimate tensile strength increased from about 19 MPa to 36 MPa and elastic modulus from about 550 MPa to 1103 MPa; process optimum was linked to layer thickness, infill and raster angle	Printability, nozzle wear and anisotropic layer bonding remain critical	Good candidate for low-volume fixtures, jigs and non-safety interior prototypes	(Anerao et al., 2023)
Impact-modified PLA/biochar	Submicron and coarser biochar in PLA with impact modifier	Injection molding with in-mold annealing and accelerated ageing	Submicron biochar improved impact response; PLA/impact-modifier/5 wt.% biochar synergy produced very high toughness improvement in one system	Aging, annealing and impact modifier package must be optimized together	A path to bio-based interior parts if heat resistance and ageing targets are met	(Brdlik et al., 2024)
Epoxy/biochar composite	Low wt.% biomass-derived biochars	Thermoset mixing and cured coupon testing	A selected 4 wt.% biochar increased tensile and flexural properties substantially; higher loading reduced performance because of weak bonding and defects	Low processing viscosity and dispersion are difficult as loading rises	Useful for coatings, adhesive layers, brackets, inserts and hybrid laminate matrices after fatigue validation	(Minugu et al., 2021)
Epoxy/biochar composite, 2026 study	Up to 9 wt.% biochar	Thermoset composite testing	Tensile strength increased from 22.7 MPa to 29.2 MPa; flexural strength increased from 58 MPa to 70.1 MPa at 9 wt.%	Effect size is matrix- and biochar-specific; toughness and environmental ageing remain underreported	Moderate reinforcement is credible for secondary thermoset parts and coatings	(Venkata Suresh et al., 2026)
PA6/biocarbon composite	20-30 wt.% biocarbon from wheat straw or plastic-paper waste	Extrusion and injection molding	At 30 wt.%, tensile modulus increased by about 34-37%, flexural modulus by about 46-48%, HDT increased up to 186 deg C and the material was about 10% lighter than selected mineral-filled references	Long-term hydrothermal ageing and full OEM validation remain needed	Strongest near-term path for engineering plastic components requiring heat resistance and lower density	(Ghosh et al., 2026)
Rubber/biochar composite	Biochar considered as partial carbon-black substitute	Rubber compounding and vulcanization literature	Biochar offers high surface area, stability and sustainability potential as a carbonaceous filler	Rubber performance requires abrasion, fatigue, hysteresis and dynamic ageing data	Potential for seals, damping parts and partial CB substitution, but tire-grade adoption requires extensive durability testing	(Karunanayake et al., 2025)

3.4 Mechanisms and Property-Loading Windows

The engineering response of a biochar composite is governed by the balance between beneficial reinforcement mechanisms and defect-generating mechanisms. Beneficial mechanisms include particle load transfer, mechanical interlocking inside pores, crack deflection, restriction of polymer-chain mobility, nucleation of crystalline regions and formation of a thermally stable char barrier. Defect mechanisms include agglomeration, void formation, poor wetting, excessive matrix immobilization, viscosity-induced fiber or filler misalignment and local stress concentration.

The conceptual response map in Figure 2 summarizes these competing mechanisms. At low loading, fine and well-wetted biochar can improve strength and toughness because particles are sufficiently separated and interfacial area is high. At intermediate loading, stiffness, heat resistance and char formation dominate. At high loading, agglomeration and melt-viscosity rise can reduce processability and damage impact behavior. This

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explains why studies often report a property optimum rather than monotonic improvement.

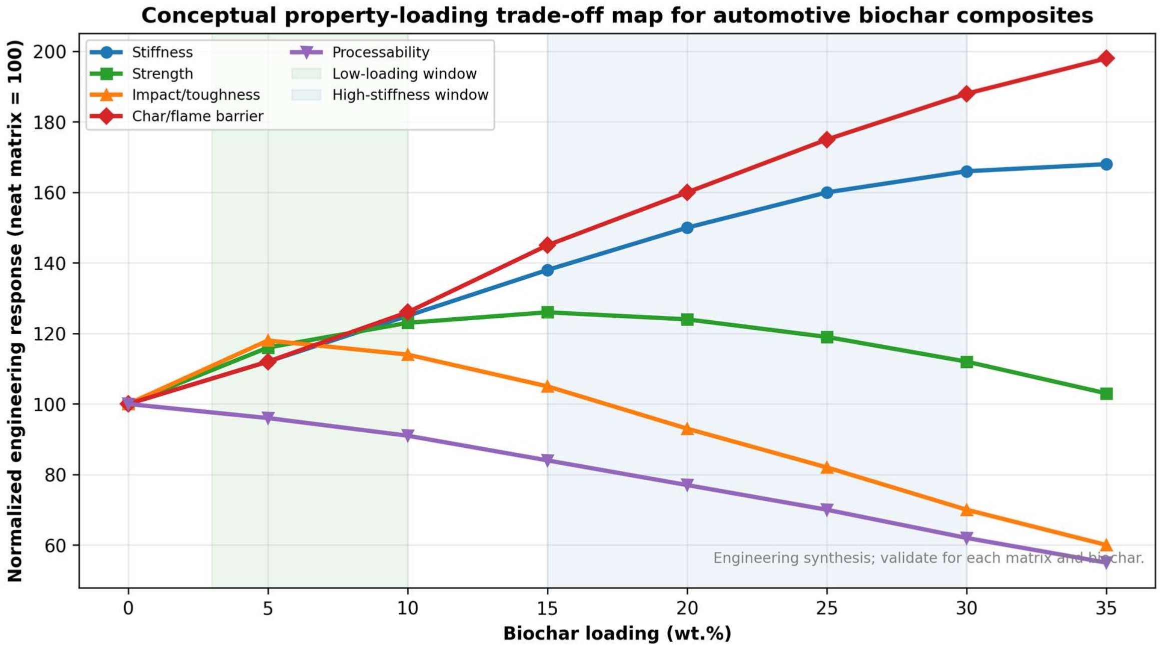

Figure 2. Conceptual Property-Loading Trade-Off Map for Biochar Composites. The Curves Synthesize Trends Reported Across Different Polymer Matrices and Are Intended as Engineering Design Guidance

Table 5. Technical Design Rules Derived from the Property-Loading Analysis

Design variable	Low-risk range or condition	Primary benefit	Failure signal during development	Corrective engineering action
Loading level	5-10 wt.% for toughness-sensitive PLA/epoxy; 15-30 wt.% for stiffness-dominated PP/PA6 when processable	Balances strength, toughness and viscosity	Impact strength drops sharply or melt pressure rises	Reduce loading, use finer controlled PSD, improve interface or hybridize with elastomer/fiber
Particle size	Submicron to low-micron for strength and toughness; controlled tens of microns for cost-sensitive molding	High interfacial area and smooth molded surface	Agglomerates, nozzle clogging, high scatter in strength	Classify powder, deagglomerate, use masterbatch, add dispersant or compatibilizer
Surface chemistry	Matrix-compatible polarity; MAPP for PP and selected oxidation/plasma treatment for polar matrices	Improved wetting and stress transfer	Clean particle pull-out on fracture surface	Add coupling agent, grafting, silane or plasma/oxidative treatment
Ash content	Stable batch-specific target with low moisture uptake	Can support stiffness and flame response	Tool wear, inconsistent color, high moisture and odor	Set incoming ash specification; wash or classify feedstock; qualify wear and VOC
Moisture level	Low and controlled before compounding	Avoids voids and hydrolysis	Splay, bubbles, molecular-weight loss in PLA/PA6	Dry filler and resin; monitor Karl Fischer moisture and MFI
Porosity	Moderate accessible porosity for interlocking	Improved interface and char barrier	Excessive additive absorption or high viscosity	Tune pyrolysis/activation; pre-wet with matrix-compatible additive
Processing temperature	Below degradation limit of matrix and surface functionality	Stable melt and consistent molecular weight	Odor, discoloration, torque instability	Optimize temperature profile and residence time; use antioxidant package

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Design variable	Low-risk range or condition	Primary benefit	Failure signal during development	Corrective engineering action
Hybrid reinforcement	Biochar plus natural fiber, glass fiber, talc, FR package or impact modifier	Multi-objective performance	One property improves while another fails	Use design-of-experiments and multi-criteria optimization

3.5 Proposed Automotive Biochar Composite Readiness Index

To convert the literature review into an engineering decision aid, this article proposes an Automotive Biochar Composite Readiness Index (ABCRI). The index is not a replacement for material qualification; it is a screening tool to compare candidate matrix-biochar families before expensive part-level validation. Eight equally weighted dimensions are used: stiffness, toughness, heat resistance, fire/smoke behavior, processability, sustainability value, cost potential and technology maturity. Figure 3 shows a radar representation of the proposed scores. PP/WPC-biochar scores strongly in processability, cost and maturity because PP compounding and automotive interior molding are established. PA6/biocarbon scores strongly in heat resistance and stiffness, making it attractive for under-hood or thermally demanding components. PLA/biochar scores strongly in sustainability and additive-manufacturing opportunity but requires heat-resistance and ageing improvement. Rubber/biochar has high sustainability promise, but automotive tire-grade or dynamic-seal deployment requires more fatigue and abrasion data.

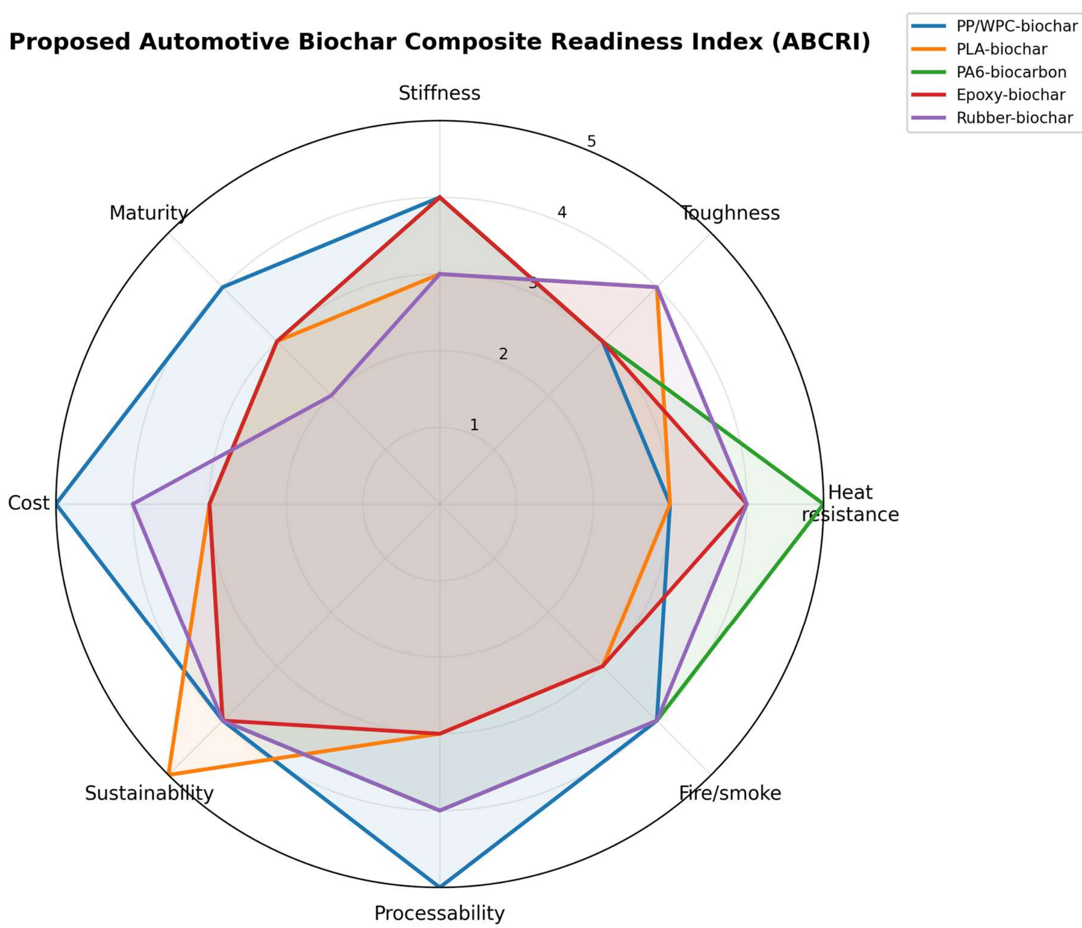

Figure 3. Proposed Automotive Biochar Composite Readiness Index (ABCRI). Scores Are Engineering Judgments from 1 (Low) to 5 (High) Based on Literature Maturity and Automotive Constraint

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Process risk must be evaluated in parallel with the readiness index. Figure 4 illustrates how loading level and particle size interact with agglomeration, melt-pressure rise and surface-defect probability. The map is intentionally conservative: small particles are beneficial for interface area but increase dusting and agglomeration risk; coarse particles are easier to feed but may behave as stress concentrators; high loading increases modulus and char barrier but increases melt pressure and can reduce impact toughness.

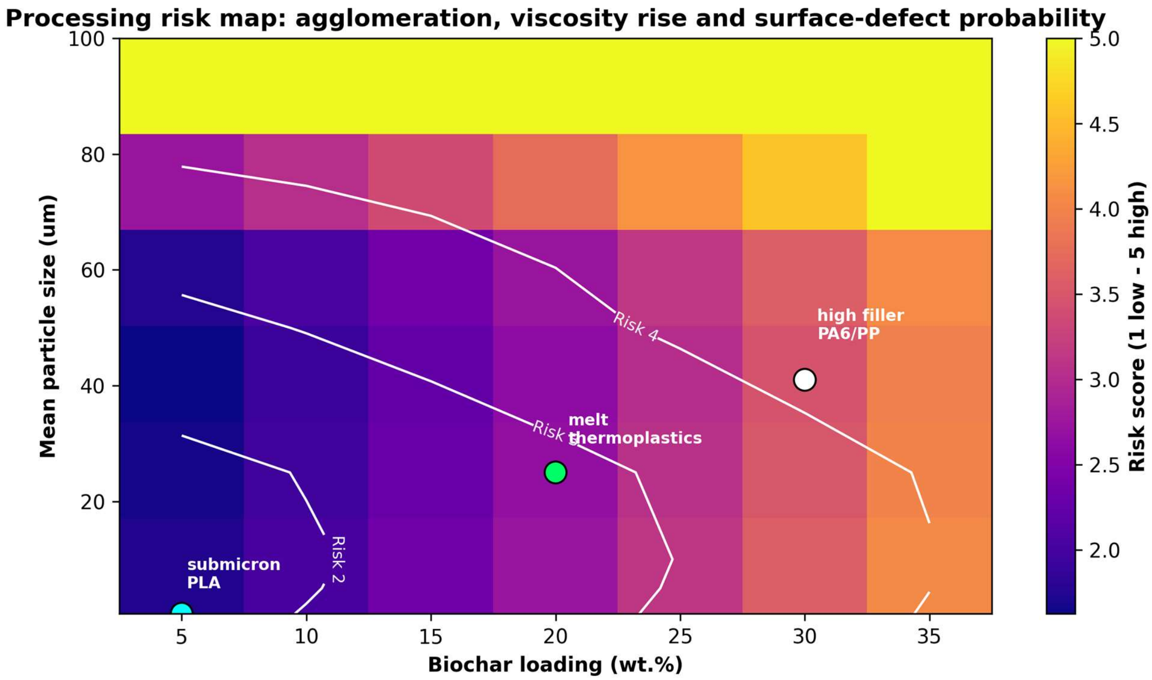

Figure 4. Processing risk map for biochar loading and particle size. The risk field is an engineering synthesis, not an experimental dataset, and should be calibrated for each processing line.

Table 6. Proposed ABCRI Scoring Logic and Interpretation.

Dimension	Score 1	Score 3	Score 5	Evidence type needed for upgrade
Stiffness	No significant modulus gain or high scatter	Moderate modulus gain with acceptable scatter	High modulus gain with stable batch-to-batch data	Tensile/flexural modulus, DMA, CLTE and CAE correlation
Toughness	Severe impact reduction	Acceptable impact after optimization	Impact equal or superior to incumbent material	Notched impact, puncture, low-temperature impact and fracture-surface analysis
Heat resistance	HDT near neat matrix or reduced	Moderate HDT or VST improvement	HDT meets component class requirement with ageing margin	HDT, VST, thermal cycling, creep and heat ageing
Fire/smoke	No flame benefit or high smoke	Partial pHRR or burn-rate reduction	Meets target flame, pHRR and smoke limits	UL-94 or FMVSS equivalent, cone calorimetry, smoke density and toxicity screening
Processability	Unstable feed, high torque or defects	Requires narrow processing window	Stable extrusion/injection/FDM with production cycle time	MFI, capillary rheology, torque, screw pressure and defect audit

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Dimension	Score 1	Score 3	Score 5	Evidence type needed for upgrade
Sustainability	No feedstock traceability or high transport burden	Renewable feedstock with partial LCA data	Verified waste-derived feedstock and carbon accounting	ISO 14040/14044 LCA, mass balance, feedstock certification and end-of-life scenario
Cost	Higher than incumbent without functional benefit	Cost parity possible at scale	Cost advantage plus functional gain	Techno-economic analysis, supply agreement and tooling wear estimate
Maturity	Only exploratory coupon data	Multiple coupon studies and prototype parts	Production-scale molding and OEM validation	Pilot line data, material card, PPAP-style records and durability dossier

Table 7. ABCRI matrix-specific score summary used for Figure 3.

System	Stiff.	Tough.	Heat	Fire	Process	Sustain.	Cost	Maturity	Mean	Interpretation
PP/WPC-biochar	4	3	3	4	5	4	5	4	4.0	Near-term interior and semi-structural candidate
PLA-biochar	3	4	3	3	3	5	3	3	3.38	Promising for bio-based interiors and FDM after heat ageing control
PA6-biocarbon	4	3	5	4	4	4	3	3	3.75	Strong engineering-plastic candidate for heat-resistant components
Epoxy-biochar	4	3	4	3	3	4	3	3	3.38	Secondary structural and coating opportunity after fatigue validation
Rubber-biochar	3	4	4	4	4	4	4	2	3.63	Sustainable carbonaceous filler candidate requiring dynamic durability data

3.6 Component-level application ranking

The literature evidence does not support a single universal claim that biochar composites are ready for all automotive components. Instead, readiness depends on component duty, service temperature, safety criticality and the incumbent material. Figure 5 positions candidate applications on a qualitative map of service-temperature demand and structural duty. The near-term adoption zone is concentrated in interior and semi-structural components where black coloration, stiffness, density reduction and sustainability narrative can be used without requiring crash-critical performance.

From an engineering viewpoint, the most credible first adoption routes are interior trim, console or pillar covers, door-panel substrates, instrument-panel carrier sub-elements, low-volume FDM fixtures and selected under-hood covers using PA6/biocarbon. Battery-related parts are attractive because char formation and thermal shielding are relevant, but they demand stringent flame, smoke, dielectric, abuse and thermal-runaway validation. Crash-critical beams, seat structures and exterior safety components should be treated as long-term targets requiring hybrid reinforcement and validated crash material cards.

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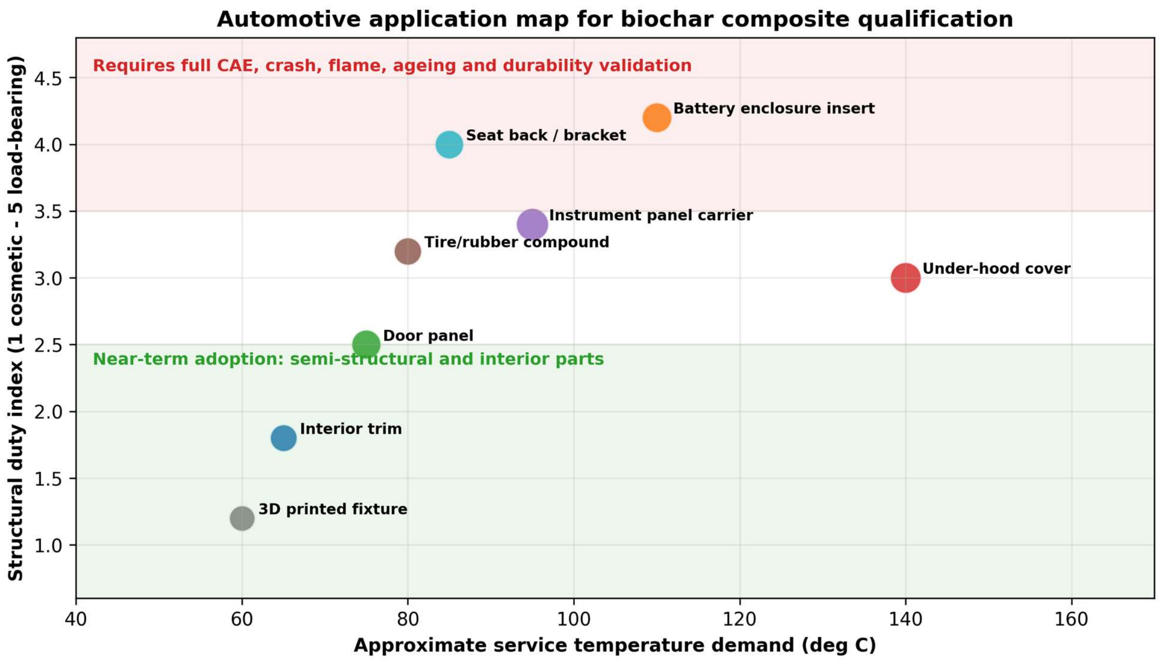

Figure 5. Automotive Application Map for Biochar Composite Qualification. Bubble Size Indicates Approximate Qualification Complexity

Table 8. Application Ranking from a Technical Engineering Perspective

Rank	Automotive application	Best candidate system	Technical value of biochar	Key risk	Recommended development route
1	Interior trim, console, pillar covers	PP/biochar or PP/WPC/biochar	Stiffness, low density, black coloration, circular-carbon content	Odor, fogging, scratch, low-temperature impact	Start with 10-25 wt.% biochar masterbatch, MAPP compatibility and interior validation
2	Door-panel substrate and instrument-panel subcarrier	PP/WPC/biochar or PA6/biocarbon hybrid	Modulus and dimensional stability with potential mass reduction	Clip retention, creep and heat ageing	Develop CAE material card, clip pull-out data and heat-humidity durability
3	FDM jigs, fixtures and low-volume interior prototypes	PLA/biochar filament	Bio-based content, stiffness and rapid customization	Nozzle clogging, anisotropic strength and heat distortion	Optimize filament diameter, 0.2 mm layer class, raster orientation and annealing
4	Under-hood covers and ducts	PA6/biocarbon	HDT, stiffness and lower density versus mineral-filled references	Hydrothermal ageing, oil exposure and vibration	Use 20-30 wt.% biocarbon; run HDT, oil soak, vibration and thermal cycling
5	Rubber seals and damping parts	Rubber with partial carbon-black replacement	Sustainability, damping tuning and potential cost benefit	Abrasion, fatigue crack growth and hysteresis control	Begin with non-tire rubber seals; validate dynamic mechanical behavior and ageing
6	Battery enclosure inserts and thermal barriers	PA6/biocarbon or epoxy/biochar with FR hybrid	Char formation, smoke reduction and thermal shielding	Electrical insulation and thermal-runaway safety	Treat as safety-critical; combine cone calorimetry, dielectric and abuse tests
7	Crash-critical structural components	Hybrid biochar/fiber composites	Possible density and sustainability benefit in hybrid designs	Impact, fatigue, crash energy absorption and material-card uncertainty	Long-term target only after coupon, subcomponent and crash-box validation

3.7 Sustainability, Mass Reduction and Life-Cycle Accounting

Biochar is attractive to automotive engineers because it links material performance with carbon-management strategy. Biomass-derived carbon can store a portion of biogenic carbon in a relatively stable solid form, and broader biochar literature identifies biochar as a carbon dioxide removal pathway when sustainable feedstock sourcing, process energy and permanence are properly accounted for (Wang et al., 2023; Lefebvre et al., 2023). However, automotive use of biochar should not automatically be labelled carbon negative. A credible claim requires a cradle-to-gate and preferably cradle-to-grave LCA that includes feedstock collection, drying, grinding, pyrolysis

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energy, co-product allocation, transport, compounding, molding, vehicle-use mass effects and end-of-life treatment.

The mass-reduction effect is also application-specific. Replacing talc or glass fiber with lower-density biocarbon can reduce composite density, as shown in PA6/biocarbon work reporting approximately 10% mass advantage compared with selected mineral-filled references (Ghosh et al., 2026). In electric vehicles, lightweighting still matters because it can reduce energy consumption, extend range or enable secondary mass reduction, but the break-even carbon effect depends on the embodied energy of the material and the electricity mix used during vehicle operation (Wang et al., 2026). For this reason, the proposed roadmap treats LCA as a qualification gate, not as a marketing add-on.

Table 9. LCA and Sustainability Checklist For Automotive Biochar Composites

LCA item	Required engineering data	Why it matters	Common pitfall	Recommended reporting output
Feedstock source	Species or waste stream, location, competing use, moisture and seasonal variability	Controls carbon accounting, ash content and supply security	Claiming waste status without documenting alternative use	Feedstock certificate and annual variability range
Pyrolysis process	Temperature, residence time, yield, energy source and co-products	Controls fixed carbon, surface chemistry and process emissions	Ignoring drying energy and heat losses	Mass and energy balance per kg biochar
Biochar permanence	Carbon fraction, stability indicator and expected in-use/end-of-life fate	Determines whether carbon-storage claims are credible	Assuming all carbon remains permanently stored	Conservative carbon-retention scenario
Composite manufacturing	Extrusion energy, injection-molding cycle, scrap, tool wear and drying	Can offset material-level carbon benefit	Ignoring higher viscosity and cycle-time penalty	Cradle-to-gate material inventory
Vehicle use phase	Part mass difference, vehicle class, lifetime distance and energy source	Quantifies operational savings from lightweighting	Using generic fuel saving factors without vehicle context	Use-phase sensitivity analysis
End of life	Recycling, incineration, landfill or energy recovery route	Controls carbon release and circularity	Assuming recycling without demonstrated separation route	End-of-life scenario matrix
Functional equivalence	Performance relative to incumbent material	Ensures fair comparison	Comparing by mass rather than function	Functional unit such as one qualified door-panel substrate
Uncertainty	Feedstock, energy mix, lifetime distance, density and performance scatter	Reflects realistic industrial decision-making	Presenting a single deterministic carbon number	Monte Carlo or scenario-based sensitivity plot

Table 10. Sustainability-Performance Trade-Off Matrix for Biochar Adoption.

Decision factor	Positive driver	Negative driver	Engineering decision
Density	Biochar can be lighter than mineral fillers	High loading can increase viscosity and wall thickness needs	Measure density at part level and compare by functional stiffness
Carbon storage	Biogenic carbon may be retained in durable parts	Pyrolysis energy and end-of-life oxidation reduce benefit	Use conservative LCA with transparent allocation
Recyclability	PP/biochar and PA6/biocarbon may remain mechanically recyclable	Contamination, odor and black color can reduce value	Run multiple extrusion cycles and odor/fogging after recycling
Circular feedstock	Agricultural and paper-plastic waste streams add circularity	Feedstock variability can destabilize properties	Set feedstock specification and batch incoming QC
Replacement of CB or talc	Potentially lower embodied energy and density	May not match abrasion or stiffness in all systems	Use partial replacement and hybrid filler packages first

3.8 Industrialization and Qualification Roadmap

Laboratory demonstrations often stop at tensile, flexural and thermal data. Automotive

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deployment requires a broader evidence package. Figure 6 proposes a staged roadmap beginning with feedstock standardization and ending with vehicle-level validation and end-of-life accounting. The central principle is that biochar must be treated as a controlled engineering filler, not as a generic black powder. Incoming QC should include moisture, ash, fixed carbon, particle-size distribution, tapped density and surface-area or morphology indicators.

The qualification sequence should also reflect risk level. Low-duty interior trim can move from coupon data to prototype parts relatively quickly, provided odor, fogging, scratch and flammability are acceptable. Under-hood and battery-related applications require thermal cycling, fluid exposure, flame/smoke testing and electrical-property screening. Structural components require fatigue, creep, crash simulation, strain-rate-dependent data and part-level validation.

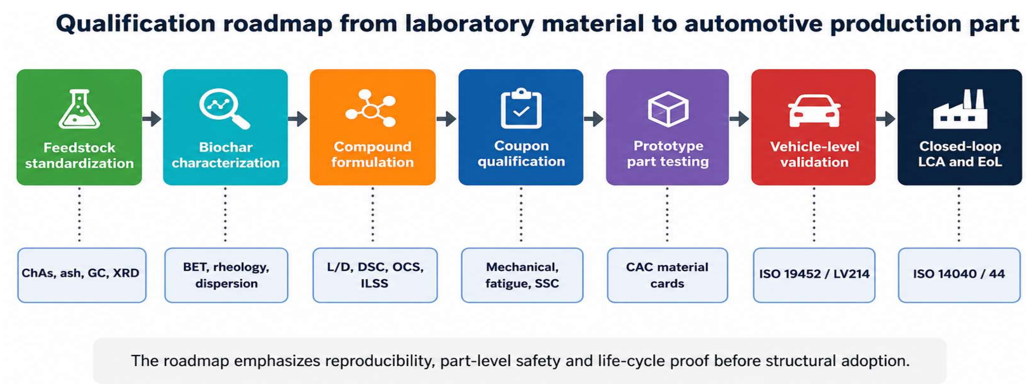

Figure 6. Qualification Roadmap from Laboratory Material to Automotive Production Part

Table 11. Recommended Test Matrix Before Automotive Part Nomination

Test category	Minimum test methods or data family	Purpose	Acceptance logic
Biochar incoming QC	Moisture, volatile matter, ash, fixed carbon by charcoal or biochar-adapted protocols; CHNS; PSD; tapped density; BET/SEM as needed	Ensure batch repeatability and protect processing line	Set internal specification limits before compounding trials
Compounding processability	MFI/MFR, capillary rheology, torque, pressure, strand stability, pellet quality	Avoid production instability, screw overload and poor dispersion	Compare with incumbent material at realistic shear and residence time
Mechanical coupons	Tensile, flexural, notched impact, puncture, DMA and creep	Generate design allowables and preliminary material card	Meet or exceed incumbent property envelope with defined safety factor
Thermal and dimensional stability	HDT, Vicat, CLTE, thermal cycling, heat ageing and warpage	Ensure dimensional control under vehicle service temperatures	Part geometry and fastening strategy determine final limits
Fire, smoke and odor	Horizontal/vertical flame screening, cone calorimetry, smoke density, VOC, odor and fogging	Protect cabin safety and customer perception	Use component-specific OEM limits rather than material-only claims
Environmental durability	Humidity, UV, oil/fuel/cleaner exposure, salt mist for assemblies and accelerated ageing	Capture real service degradation	Test after ageing, not only before ageing
Part-level validation	Mold-flow, weld-line strength, clip retention, vibration, squeak/rattle and assembly trials	Translate coupon performance into manufacturing reality	Prototype parts must pass dimensional and functional audits
Sustainability validation	Cradle-to-gate and cradle-to-grave LCA, recycled-content traceability and end-of-life route	Substantiate environmental benefit	Claims must be tied to functional unit and sensitivity analysis

3.9 Future Research Directions

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Future research should move from single-property screening toward validated material systems. The most urgent need is feedstock-to-property traceability. Without standardized reporting of feedstock, pyrolysis conditions, ash chemistry, particle-size distribution, moisture and surface area, it is difficult to compare results or scale compounding. Biochar databases for automotive grades should therefore include both chemical descriptors and processing descriptors.

A second priority is interfacial engineering. Matrix-specific coupling agents, plasma or oxidative surface treatments, bio-based compatibilizers and hybrid filler architectures should be studied using design-of-experiments methods. The goal is to define robust process windows that preserve impact toughness while increasing stiffness and heat resistance. Fracture-surface microscopy, micro-CT, dynamic mechanical analysis and rheology should be used together to connect microstructure with macroscopic behavior.

A third priority is part-level validation. Many publications report tensile or flexural coupon data, but automotive approval also depends on flow length, weld-line strength, fastener retention, warpage, creep, fatigue, odor, fogging, scratch and ageing. Future studies should therefore include prototype automotive geometries, not only standardized coupons. Finally, LCA must be integrated with materials engineering so that environmental claims are tied to qualified functional performance.

Table 12. Research Agenda for Transforming Biochar Composites Into Automotive-Grade Materials

Research gap	Technical question	Recommended experiment	Expected engineering output
Feedstock variability	Which biochar descriptors best predict composite properties?	Produce multiple biochars from controlled feedstocks and pyrolysis temperatures; characterize CHNS, ash, BET, PSD and surface chemistry	Predictive feedstock-property map and incoming QC specification
Interface design	Which coupling strategy maximizes strength without sacrificing impact?	Compare untreated, MAPP/silane, plasma and oxidized biochar across PP, PLA and PA6	Matrix-specific interfacial design rules
Rheology and processing	How does biochar affect melt pressure, cycle time and defects?	Run capillary rheology, twin-screw torque monitoring, injection trials and FDM nozzle tests	Processing window and tool-design constraints
Ageing and durability	How stable are properties after heat, humidity, UV and fluids?	Test coupons and prototype parts before and after accelerated ageing	Durability knock-down factors for CAE
Fire and smoke	Can biochar reduce pHRR and smoke without reducing toughness?	Combine cone calorimetry, UL/FM screening and fracture analysis for hybrid FR packages	Balanced flame-retardant formulation map
Crash and fatigue	Can biochar be used in energy-absorbing hybrid structures?	Create strain-rate material cards and crash-box or bracket prototypes	CAE-ready dataset and structural design limits
Recycling	Do biochar composites retain properties after multiple melt cycles?	Reprocess PP and PA6 biochar composites for 3-5 cycles and measure odor/fogging/mechanics	Closed-loop recycling feasibility
LCA integration	When is biochar reinforcement lower carbon than talc, CB or glass fiber?	Perform scenario-based LCA using functional units and actual production energy	Carbon and cost decision map for purchasing and design teams

4. CONCLUSION

This review evaluated biochar as a reinforcement for automotive composite materials using a property-process-sustainability viewpoint. The evidence supports biochar as a credible engineering filler for selected polymer systems, especially when the target functions are stiffness enhancement, density reduction, heat resistance, char formation and circular-carbon content. PP/WPC-biochar and PA6/biocarbon systems appear particularly attractive for interior and heat-resistant semi-structural applications, while PLA/biochar is promising for bio-based interiors and additive manufacturing. Epoxy and rubber systems show potential but require stronger fatigue, ageing and dynamic-performance evidence.

The main technical barrier is not the absence of reinforcement potential but the variability of biochar and the non-monotonic relation between filler loading and performance. Loading, particle size, ash content, moisture, surface functionality and compatibilization must be engineered together. Strength and impact toughness can degrade when biochar agglomerates, absorbs additives, increases viscosity or fails to wet the matrix. Therefore, biochar composites should be designed through controlled feedstock selection, particle

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classification, coupling chemistry and application-specific processing windows.

The proposed ABCRI, application ranking and qualification roadmap provide a practical framework for moving biochar composites from laboratory studies to automotive parts. Near-term adoption should focus on non-structural and semi-structural components where stiffness, appearance, flame behavior, mass reduction and sustainability benefits are valuable. Safety-critical or crash-critical components should remain long-term targets requiring hybrid reinforcement, full CAE material cards, durability validation and transparent LCA. With rigorous standardization and part-level testing, biochar can become an important reinforcement in the next generation of lightweight and lower-carbon automotive composites.

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