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Eco-Friendly Brake Pad Materials: A Comprehensive Review for Automotive Applications

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Abstract

Brake pads are critical to vehicle safety, yet conventional materials such as asbestos and copper have been linked to severe health and environmental hazards, prompting global regulatory bans. This review synthesizes findings from recent studies (2022–2026) examining the use of bio-based and agro-waste materials—including coconut shells, palm kernel shells, bamboo fibers, molluscan shell powders, and sawdust—as eco-friendly substitutes in brake pad composites. These natural fiber and particulate reinforcements consistently deliver friction coefficients of 0.35–0.49, low specific wear rates, and thermal stability up to 600 °C, while offering advantages of lower density, cost-effectiveness, and biodegradability. The paper further reviews the role of friction modifiers (carbon fiber, zeolite, MoS_2, PDMS), copper-free metallic alternatives (steel fiber, aluminum), and process optimization. Evaluation methodologies including CHASE dynamometer testing, SEM/EDX analysis, finite element simulation, and machine learning-aided formulation are discussed. Key challenges such as moisture sensitivity, fiber agglomeration, and scale-up difficulties are identified, along with future directions encompassing AI-driven design, hybrid formulations, and bio-resin systems. These advances position eco-friendly brake pads as viable replacements for conventional materials in next-generation automotive and electric vehicle platforms.

Keywords: *Index Terms—Eco-friendly brake pads, natural fibers, agro-waste composites, tribology, friction materials, sustainability, copper-free, bio-composites.*

1. Introduction

Brake pads are among the most safety-critical components in an automotive system, converting kinetic energy into heat through friction against the rotor to decelerate or stop a vehicle. For decades, asbestos served as the dominant reinforcement material due to its exceptional thermal stability and frictional properties. However, the well-documented carcinogenicity of asbestos fibers led to its global phase-out and strict legislative bans in most industrialized nations. Subsequently, copper emerged as a widely adopted filler, prized for its thermal conductivity and friction stability. Yet copper-derived wear particles have been identified as significant aquatic pollutants, prompting regulatory restrictions in regions such as California and Washington State, USA, with broader restrictions anticipated [1], [10], [11]. This convergence of regulatory pressure and environmental awareness has intensified research into sustainable, high-performance alternatives. The period from 2022 to 2026 has witnessed a surge of investigations leveraging agricultural by-products, natural fibers, and waste-derived bio-fillers—materials that are abundant, low-cost, and biodegradable. Simultaneously, advances in processing (hot-press molding), surface chemistry (chemical treatments, siloxane functionalization), testing (CHASE tribometry, SAE J661), and computational tools (machine learning, finite element analysis) have accelerated the development cycle for these green

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friction composites [2], [5], [6]. This paper presents a comprehensive review of eco-friendly brake pad materials, covering the classes of bio-based fillers and reinforcements, performance-enhancing additives, copper-free metallic alternatives, and the methodologies used to characterize and optimize these systems. The review identifies consistent performance benchmarks, recurring challenges, and emerging research directions that will shape the next generation of sustainable automotive braking solutions.

2. Traditional Materials and Regulatory Background

Early brake pads relied heavily on chrysotile and other asbestos minerals as reinforcing fibers due to their outstanding heat resistance and mechanical properties. The recognition of asbestosis, mesothelioma, and lung cancer risks associated with airborne asbestos fibers precipitated progressive regulatory action beginning in the 1980s, eventually culminating in near-total bans in Europe, North America, and much of Asia [14]. Non-asbestos organic (NAO) and low-metallic formulations subsequently replaced asbestos, with copper, brass, and other metallic fillers providing thermal management and friction stability [10]. Copper's regulatory trajectory mirrors that of asbestos. Studies documenting copper nanoparticle toxicity to salmon and aquatic invertebrates have driven phase-down mandates. Additionally, antimony trioxide (used as a synergist in flame-retardant binders), cadmium compounds, and phenolic resins with high volatile organic compound (VOC) emissions face increasing scrutiny [11], [24]. This regulatory landscape creates a compelling imperative for friction material formulators to adopt sustainable, bio-derived, or low-toxicity alternatives while maintaining the tribological and thermal performance demanded by modern braking standards.

3. Bio-Based and Agro-Waste Composites

3.1. Plant Fiber Fundamentals

Plant fibers—including jute, hemp, kenaf, bamboo, banana, and coconut coir—are gaining traction as polymer composite reinforcements across the automotive, construction, and aerospace sectors. Compared with synthetic alternatives, plant fibers offer ease of processing, lower CO_2 footprint during production, biodegradability, recyclability, and favorable thermomechanical properties [1]. As reinforcements in thermoset or thermoplastic matrices, they improve mechanical performance, thermal resistance, and surface characteristics. However, their inherent hydrophilicity—arising from hydroxyl (–OH) groups and amorphous hemicellulose regions—reduces interfacial bonding with hydrophobic polymer matrices and lowers dimensional stability in humid environments. Chemical treatments such as alkali (NaOH) mercerization, silane coupling, and benzoylation effectively reduce surface polarity and enhance fiber–matrix adhesion [1], [13].

3.2. Coconut Shell and Palm Kernel Shell

Coconut shell and palm kernel shell powders are among the most extensively investigated agro-waste fillers. Dirisu et al. [3] fabricated asbestos-free brake pads using coconut shell (CS) and oil bean stalk (OBS) particles with aluminium dross and carbon black in an epoxy matrix, compacted via square wooden moulds. The produced composites exhibited specific gravities of 1.136–1.257—significantly lighter than commercial brake pads (specific gravity 2.081)—and water absorptivities of 0.95–2.17%. The formulation based on 212 µm CS particles achieved optimal performance: compressive strength 120.5 MPa, hardness 29.6 HV100, wear resistance 0.099 mm/mm^3, and specific wear rate 1.00 mm^3/Nm. EDX and SEM analyses confirmed strong interfacial bonding and homogeneous particle distribution at this particle size [3]. INJO et al. [15] investigated composites combining periwinkle shell (PS) and palm kernel shell (PKS) in epoxy at optimized particle sizes of 100–125 µm in various PS:PKS ratios. Fine particles reduced porosity and improved wear resistance and hardness (up to 75 HRC for PS). The best formulations achieved coefficients of friction (COF) between 0.35 and 0.44 and wear rates of 0.017–0.170 mm/min, comparable to commercial brake pads. Thermal analysis by thermogravimetric analysis (TGA) confirmed PS stability above 600 °C, while PKS undergoes multi-stage decomposition between 54–538 °C, illustrating the complementary thermal profiles of the two fillers [15].

3.3. Agricultural By-Products: Sugarcane, Banana, and Hemp

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Emmanuel et al. [7] reviewed the performance of bio-based brake pads incorporating palm kernel shell (compressive strength up to 96.2 MPa), coconut shell (hardness up to 186.2 BHN), sugarcane bagasse ash, and banana peel ash. Silica-rich ashes from sugarcane and banana peels enhance thermal stability through network-forming oxide interactions within the composite matrix. The review emphasizes the importance of optimizing filler particle size distributions and surface treatments to achieve uniform dispersion and strong adhesion in the composite microstructure [7]. Devan et al. [8] pioneered the use of coconut fiber and sawdust as co-reinforcements combined with abrasives and friction modifiers. Hardness, compression, wear (pin-on-disc), and TGA tests confirmed satisfactory mechanical properties and excellent thermal stability at elevated temperatures, meeting organic brake pad industry standards. The study highlights the importance of the high strength-to-weight ratio and thermal stability inherent in these natural fiber systems [8].

3.4.Molluscan Shell Waste Fillers

Jiyas et al. [12] explored an innovative class of eco-filler derived from waste molluscan shells (Perna perna, Meretrix casta, gastropod, and Rocellaria dubia), naturally rich in calcium carbonate. Shells were incorporated into composites alongside permanganate-treated kenaf fiber reinforcement, with cashew friction dust and graphene oxide as friction modifiers. FTIR, XRF, and XRD confirmed the elemental and phase purity of the shell powders; TGA demonstrated their thermal stability. Five composite formulations were tested by pin-on-disc (ASTM G99) and CHASE tribometer (SAE J661a), including fade and recovery assessments. Perna perna shell composites outperformed the calcium carbonate control in tribological excellence, friction stability, and wear resistance, establishing molluscan shell waste as a compelling next-generation green bio-filler [12].

3.5.Bamboo Fiber Composites

Nazee et al. [13] examined the tribological role of PDMS (polydimethylsiloxane) as a lubricant additive in brake pads reinforced with benzoyl-treated Pseudoxytenanthera stocksii bamboo rhizome fibers. Tribological testing via CHASE tribometer (SAE J661a) revealed that low-viscosity PDMS provided superior friction stability compared to higher-viscosity variants, which, while improving lubrication, reduced the COF and increased wear rates. The study underscores the critical importance of lubricant viscosity in tuning the tribological response of bio-fiber composites [13]. Hemanth et al. [2] performed ANSYS simulations comparing several eco-friendly alternatives (palm kernel fiber, coconut coir, bamboo, banana peels) to predict their performance as asbestos replacements, demonstrating the potential of simulation tools in early-stage eco-formulation screening [2].

3.6.Apricot Kernel Shell

Unal et al. [18] evaluated apricot kernel shell—an agricultural waste—as a bio-material additive for brake pad compositions tested on a dynamometer. Varying granule sizes and weight fractions were assessed. While apricot kernel shell slightly elevated noise levels, it consistently improved the COF, demonstrating its potential as an economical and environmentally friendly additive material in NAO formulations [18].

4. Friction Modifiers and Performance Optimization

4.1.Abrasive Particle Surface Treatment

Chauhan et al. [4] investigated siloxane-treated alumina (Al_2O_3) particles in NAO copper-free brake pads. Untreated abrasive particles exhibit poor adhesion to the resin matrix, causing them to dislodge under shear during braking—contributing to three-body abrasion and elevated noise and vibration (NV). Siloxane treatment improved filler–matrix adhesion, extending the retention of abrasive particles on the tribosurface and enhancing friction control. NV performance tests per SAE J2521 on an NV test rig showed an average reduction of 2–3 dB(A) in overall sound pressure level (SPL) for siloxane-treated formulations compared to untreated controls, validating the hypothesis that improved adhesion reduces brake squeal [4].

4.2.Carbon Fiber Content Optimization

Zeng et al. [22] systematically varied carbon fiber (CF) content from 0 to 12 wt.% in eco-friendly NAO brake pads fabricated by hot-press molding. At 6 wt.% CF, the formulation achieved the optimal balance: lowest COF (0.37 at room temperature; 0.21

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at 300 °C), lowest wear rate (3.14×10^{-4} mm³/Nm at RT; 1.39×10^{-4} mm³/Nm at 300 °C), highest hardness (105.67 HRM), and highest flexural strength (14.16 MPa). SEM microstructural analysis confirmed uniform fiber dispersion and strong fiber–matrix interfacial bonding at this content. Exceeding 12 wt.% CF led to fiber agglomeration, microstructural defects, and significantly deteriorated mechanical and tribological properties [22].

4.3.Zeolite and Molybdenum Disulfide Hybrid Systems

Raghunathan et al. [19] developed hybrid fiber brake pads incorporating zeolite (high thermal resistance) and MoS_2 (exceptional solid-phase lubrication). Three formulations with varying Zeolite:MoS_2 weight ratios were assessed by CHASE testing per IS2742-Part-4/SAE J661. Formulation ZRBP-2 yielded the highest performance COF (μ = 0.43), acceptable fade COF (μ_{fade} = 0.353), and recovery COF ($\mu_{recovery}$ = 0.389). SEM analysis of worn surfaces confirmed the formation of a stable tribofilm attributable to the synergistic interaction of the two additives. These findings validate hybrid mineral-lubricant combinations as effective strategies for achieving friction stability over a wide temperature range [19].

4.4.Boron-Based Additives

Gunduz et al. [26] examined boric acid and borax decahydrate as refined boron additives in conventional brake pad matrices (Novolak resin, copper, alumina, graphite, brass, zirconium silicate, sulfates). Porosity increased with boron content, reducing density, while hardness increased to maxima at 2.5 wt.% for boric acid and 5.0 wt.% for borax decahydrate before declining at higher loadings. A linear correlation between hardness and wear resistance was demonstrated. SEM, EDX, and 3D profilometry analyses revealed oxide tribolayer formation and plastic deformation at wear track edges. Overall, optimal boron concentrations significantly enhanced frictional performance [26].

4.5.Molding Process Optimization

Partovinia et al. [25] applied analysis of variance (ANOVA) to quantify the individual and interaction effects of molding temperature, pressure, and time on normal and hot friction coefficients of brake pads. Pressure was the dominant factor affecting normal friction, while hot friction was strongly influenced by all three factors and their mutual interactions (temperature–pressure, temperature–time, and pressure–time). Optimization identified a molding temperature of 170 °C, time of 290 s, and pressure of 350 kgf/cm² as yielding the highest normal and hot friction coefficients of 0.49 and 0.41, respectively—providing a process engineering framework directly applicable to eco-friendly composite manufacturing [25].

5. Copper-Free Metallic Alternatives

5.1.Steel Fiber Reinforcement

Mollaei et al. [21] investigated low-metallic brake pad formulations reinforced with 10–30 wt.% steel fibers as a direct copper replacement, fabricated by hot molding followed by post-cure. CHASE friction testing per SAE J661 evaluated normal and hot friction coefficients, wear rate, and shear strength. The 15 wt.% steel fiber formulation delivered the most balanced performance: hot COF of 0.468 and normal COF of 0.439, indicating low sensitivity to operating conditions, along with the lowest wear rate (4.236%) and excellent thermal stability. These results demonstrate that steel fiber reinforcement can substitute copper in brake pads without compromising tribological performance or durability [21].

5.2.Aluminum vs. Copper

Zheng et al. [23] conducted a systematic comparison of copper and aluminum additions in resin-based brake materials. Both elements enhanced heat resistance, hardness, and impact strength; however, aluminum-containing formulations exhibited superior heat resistance, lower density (advantageous for lightweighting), and markedly better tribological properties at elevated temperatures—achieving higher COF than copper-containing counterparts. Critically, aluminum promoted the formation of a stable friction film at the sliding interface, reducing surface roughness. Microbiological assays demonstrated that copper wear debris induced membrane disruption and cell death in E. coli, while aluminum-containing materials exhibited no detectable toxicity. The optimized copper-free, aluminum-reinforced brake material showed a stable COF of 0.53–0.60, confirming substantial application potential for environmentally responsible

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formulations [23].

6. Testing Methodologies and Evaluation

6.1. Chase Dynamometer and Standard Tests

The CHASE (Chase Machine & Engineering) friction test machine, operating per SAE J661a, is the industry-standard method for evaluating fade, recovery, wear, and friction stability of brake pads under controlled thermal and load cycles. Multiple studies reviewed herein employed CHASE testing to compare eco-friendly formulations with commercial references, providing directly comparable tribological benchmarks [12], [13], [19], [21]. IS2742 (Parts 1–4), equivalent to SAE J661, is the adopted standard in the Indian automotive context [17], [19].

6.2. Mechanical and Thermal Characterization

Standard mechanical characterization protocols for brake pad composites include compressive strength (Universal Testing Machine), hardness (Vickers HV, Rockwell HRM/HRC, and Brinell BHN scales), water absorptivity, and specific gravity measurements. Thermal characterization employs TGA for decomposition profiles and automated Lee's Disc apparatus for thermal conductivity. SEM coupled with EDX provides microstructural and elemental analysis of both as-fabricated composites and worn surfaces, revealing interfacial bonding quality, fiber dispersion, tribofilm formation, and failure modes [3], [12], [15], [22].

6.3. Machine Learning-Aided Formulation

Quamar et al. [16] applied four ML algorithms—K-Nearest Neighbors (KNN), Support Vector Machine (SVM), Random Forest (RF), and Gradient Boosting Machine (GBM)—to tribological datasets from brake inertia dynamometer tests. The Gradient Boosting Regressor (GBR) achieved superior COF prediction accuracy. Feature importance analysis identified acetone extraction and deceleration as the most influential variables in COF prediction, offering actionable insights for formulation design and process control [16]. Kisanrao et al. [5] further noted the emerging role of artificial intelligence and nanotechnology in accelerating the discovery of innovative brake pad materials [5].

6.4. Finite Element Analysis

Maciel et al. [20] employed ANSYS finite element software to simulate the behavior of drum brake linings in a rear-axle heavy vehicle application, comparing a commercial lining with a coconut shell-reinforced biomaterial lining across five transient thermal and static simulation stages. Complex modal analysis extracted eigenvalues associated with brake squeal propensity. Biomaterial linings demonstrated not only comparable structural integrity to commercial counterparts but also reduced brake squeal-inducing eigenvalue magnitudes, providing a computational validation pathway for eco-friendly brake lining development without extensive physical prototyping [20].

6.5. Multi-Criteria Ranking

Balaji et al. [17] integrated the Analytical Hierarchy Process (AHP) with multiple ranking methods—Extension Evaluation Method (EEM), Complex Proportional Assessment (COPRAS), Preference Selection Index (PSI), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)—to evaluate four OEM brake pad products for Indian passenger cars. Performance parameters from IS2742 testing (fade %, recovery %, wear loss, COF variants) were synthesized into a decision matrix. This hybrid ranking framework demonstrated that a budget-friendly brake pad (OE4) outperformed premium alternatives in overall composite performance, illustrating the utility of multi-attribute decision analysis in brake pad procurement and benchmarking [17].

7. Comparative Performance Summary

Table I summarizes the key tribological and mechanical performance characteristics of representative eco-friendly brake pad formulations from the reviewed literature.

Table I Comparative Performance of Eco-Friendly Brake Pad Materials

Filler/Reinforcement	Ref.	COF Range	Wear Rate	Thermal Stability
Coconut Shell (212 µm)	[3]	0.35–0.44	0.099 mm/mm^3	Good bonding

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Palm Kernel Shell	[15]	0.35–0.44	0.017–0.17 mm/min	>600 °C (PS)
Perna perna Shell	[12]	Stable	Low	Excellent
6 wt.% Carbon Fiber	[22]	0.37 (RT)	3.14×10^{-4} mm^3/Nm	Up to 300 °C
15 wt.% Steel Fiber	[21]	0.44–0.47	4.24%	Excellent
Al-reinforced (Cu-free)	[23]	0.53–0.60	Stable	Superior to Cu
Zeolite+MoS_2 (ZRBP-2)	[19]	0.43 (perf.)	Low	High
Bamboo + low-vis PDMS	[13]	Stable	Low	Good

8. Challenges And Future Directions

8.1.Current Challenges

Despite significant progress, several challenges impede the large-scale adoption of eco-friendly brake pads. (1) Moisture sensitivity: Natural fibers inherently absorb moisture due to hydroxyl groups, leading to swelling, fiber–matrix debonding, and reduced mechanical performance in humid environments. Chemical treatment reduces but does not eliminate this issue [1]. (2) Consistency and scalability: Agro-waste particle size, morphology, and chemical composition vary with crop variety, region, and season, complicating batch-to-batch reproducibility and scale-up from laboratory to industrial production [7], [15]. (3) Noise and vibration: Some bio-fillers (e.g., apricot kernel shell at higher loadings) slightly increase brake noise, requiring optimization of formulation and surface treatment to minimize NV signatures [18]. (4) Fiber agglomeration: Excessive carbon fiber loading (>12 wt.%) causes fiber clustering, creating stress concentration sites that degrade hardness and flexural strength [22]. (5) Resin sustainability: Phenolic resins, the dominant binder in friction materials, present VOC emission and processing concerns. Their replacement with bio-phenolics or other eco-resins remains an active and partially unresolved research challenge [11], [24].

8.2.Future Research Directions

(1) Hybrid bio-formulations: Combining multiple agro-waste fillers with complementary properties (e.g., thermal stability from periwinkle shell + mechanical strength from palm kernel shell + friction modifier from graphene oxide) can synergistically exceed individual material limitations [15]. (2) AI and machine learning: ML algorithms—particularly gradient boosting methods—show strong predictive capability for COF from material and process variables, enabling data-driven formulation optimization and reducing experimental iterations [16]. Physics-informed neural networks could further integrate tribological mechanisms with material property predictions. (3) Advanced bio-resins: Development of bio-phenolics from lignin, cashew nut shell liquid (CNSL), or other bio-derived phenol precursors can replace synthetic phenolic resins while maintaining thermal and mechanical performance—completing the eco-friendly transition of the full formulation [11], [24]. (4) Electric vehicle (EV) applications: EV braking systems rely heavily on regenerative braking, resulting in lower frequency and severity of friction braking events. This altered duty cycle may favor lightweight, lower-wear eco-composites, but thermal management during occasional high-demand stops must be validated under EV-specific test protocols. (5) Life-cycle assessment (LCA): Comprehensive LCAs quantifying the full environmental footprint—from raw material extraction through manufacturing, service life, and end-of-life disposal—are necessary to substantiate the sustainability claims of bio-based formulations against conventional alternatives. (6) Nanotechnology integration: Nano-reinforcements such as graphene oxide, carbon nanotubes, and nano-

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silica at low loadings (0.1–1.0 wt.%) may enhance interfacial bonding, thermal conductivity, and tribological performance without compromising eco-credentials [5].

Conclusions

This review has comprehensively surveyed the landscape of eco-friendly brake pad materials from 2022 to 2026, demonstrating that bio-based and agro-waste composites can match and, in specific attributes, exceed the performance of conventional asbestos-based and copper-containing brake pads. Key conclusions are as follows:

- Agro-waste fillers (coconut shell, palm kernel shell, periwinkle shell, molluscan shells) consistently achieve COF values of 0.35–0.49, specific gravity reductions of 30–45% relative to commercial brake pads, and thermal stability up to 600 °C.
- Optimal fiber/filler loading exists for each system: 6 wt.% CF, 15 wt.% steel fiber, and 100–125 µm particle sizes for shell composites represent performance optima identified in the reviewed literature.
- Aluminum represents a viable, non-toxic alternative to copper, offering superior high-temperature tribological properties and zero aquatic toxicity.
- Process optimization (molding temperature, pressure, cure time) and surface treatment (siloxane functionalization, chemical fiber treatment) are critical enablers that bridge the gap between laboratory performance and commercial viability.
- Machine learning and finite element simulation are maturing as complementary tools to accelerate formulation screening and design validation, reducing reliance on costly empirical testing.

The transition to eco-friendly brake pads is not merely a regulatory compliance exercise; it represents an opportunity to integrate circular economy principles—converting agricultural and industrial waste into high-value safety components—while simultaneously reducing the automotive industry's contribution to heavy metal pollution, particulate emissions, and occupational health risks. With continued progress in hybrid formulations, bio-resin binders, and AI-assisted design, eco-friendly brake pads are poised for mainstream adoption across conventional and electric vehicle platforms in the near future.

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