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Research Article

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From Palm-Industry Residues to Climate-Resilient Roads: Bio-Asphalt Chemistry, Tropical Pavement Distress, RAP Circularity and Engineering Readiness-A Critical Review

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ABSTRACT

Palm-derived resources are increasingly examined as additives for road asphalt, but the designation "bio-asphalt" masks major differences among vegetable oils, fatty derivatives, ash, fibres, clinkers and biochars. This critical qualitative review synthesises recent pavement research through a function-specific framework connecting feedstock processing, binder chemistry, rheology, mixture performance and service conditions in tropical climates. The discussion distinguishes direct oil-palm evidence from analogues involving other waste oils and biomass-derived modifiers. Palm-derived liquids may restore binder mobility or improve workability, but excessive softening threatens rutting resistance under persistent high temperatures. Palm ash, clinker, fibre and biochar can instead modify mastic structure, aggregate skeleton, drainage stability or reinforcement, while introducing risks involving particle variability, stiffness, adsorption and wet adhesion. The review further examines high reclaimed-asphalt-pavement mixtures, ageing, coupled hot-wet traffic exposure, life-cycle assessment and life-cycle cost. Three conceptual Figures, a provisional material-selection and readiness matrix, and a staged qualification protocol are developed. Existing laboratory studies justify selective trials but do not establish generalized field durability or engineering-standard equivalence. Tropical deployment should therefore prioritize residual feedstocks, chemically and physically reproducible processing, multi-distress validation and monitored pilot sections over simple bio-content targets.

Keywords: Palm Oil, Bio-Asphalt, Tropical Pavements, Rutting, Fatigue, Moisture Damage, Biochar, Palm Oil Fuel Ash, Reclaimed Asphalt Pavement, Circular Economy

JEL Classification: L74, Q53, Q54, Q56, R42

Introduction

Tropical-Road Performance as a Sustainability Problem

Road pavement is an engineered climate interface, not merely a convenient outlet for agricultural residues. Traffic loads are transmitted through temperature-sensitive viscoelastic layers whose stiffness and cohesive integrity change as the surface warms, oxygen diffuses and water reaches aggregate–binder contacts. Tropical networks commonly experience long warm seasons, high daytime pavement temperatures, intense rainfall events and construction windows interrupted by precipitation. These mechanisms interact: a wet mixture can lose aggregate adhesion just as axle loading generates shear deformation, and previously oxidized layers can become vulnerable to fatigue once moisture accelerates local cracking. Climate change adds uncertainty to temperature extremes, precipitation intensity and the timing of maintenance demand. Consequently, an asphalt additive cannot be described as resilient merely because one laboratory test improved; it must maintain a satisfactory response across interacting failure mechanisms and realistic exposure durations [1-3]. A dedicated 2024 review of climate-resilient pavement design identifies warming, flooding and urban-heat-island exposure as distinct adaptation pressures; its synthesis supports using site-specific climatic and structural criteria rather than assigning resilience on the basis of additive origin alone [4].

The engineering consequences of failure are systemic. Rutting holds surface water and increases splash and aquaplaning

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risk; cracks admit moisture and promote base deterioration; ravelling creates loose aggregates and accelerates surface loss. Each distress generates maintenance demand, lane closures, construction fuel consumption and replacement material use. A bio-based mixture with modestly lower embodied carbon at production could have a worse total impact if its service life is shortened. Conversely, an intervention that modestly increases initial processing energy might perform favourably over several rehabilitation cycles if durability is independently demonstrated. This review therefore evaluates material function and pavement-life performance together, and it treats climate-resilience claims as hypotheses that must be tested with both mechanistic measurements and in-service observations rather than as inherent characteristics of renewable feedstocks [5-7].

Palm-Industry Materials and the Unresolved knowledge Gap

Oil palm value chains generate edible and industrial oils, refining fractions, shells, fibres, combustion ashes, clinkers and carbonaceous residues. These streams differ fundamentally in polarity, viscosity, porosity, density, reactive surface chemistry and potential contaminant content. Palm-derived liquid can behave as a fluxing agent or rejuvenator within a petroleum binder, whereas fuel ash is mainly a particulate mastic constituent, mesocarp fibre is a discrete reinforcement and palm clinker can substitute portions of the aggregate skeleton. Biochar behaves as a carbonaceous high-surface-area solid, not as an oil substitute. Earlier reviews successfully mapped the breadth of palm-derived uses, but broad biomass classifications can obscure which measured improvement originates from chemical rejuvenation, physical particle packing, mixing sequence, or a change in aggregate structure. Such distinctions directly determine optimal dosage and appropriate quality assurance [8-11].

Publication volume also conceals a translation gap. Most palm-asphalt studies remain at laboratory binder, mastic or mixture scale; many reports Marshall stability, penetration, softening point or a limited fatigue or rutting index. These outputs are useful screening indicators but they do not establish behaviour under a tropical combination of heavy traffic, solar ageing, intense wetting and plant-to-plant production variation. Results from chemically modified waste cooking oil or non-palm biochars provide valuable mechanistic analogues, yet they cannot certify an untested palm feedstock. Palm-derived materials also compete in availability, processing requirements and economic value. Consequently, this article addresses a narrower question than whether palm residues can be placed in asphalt: under which documented processing and exposure conditions can a specific palm-derived input plausibly improve whole-pavement performance without transferring the environmental burden elsewhere? [9,12-14].

Aim, Research Questions and Contribution

The aim is to integrate chemical, rheological, mechanical, hydrological and circular-economy evidence into a critical material-selection system for tropical road agencies. The review asks which feedstocks are best interpreted as rejuvenators, fillers, aggregates or reinforcement; which chemical mechanisms plausibly explain their effects; which properties trade off against rutting and wet adhesion; how they could interact with reclaimed asphalt pavement (RAP); and what testing and procurement conditions could justify progressive deployment. The proposed contribution is a processing–function–performance–readiness framework with explicit tiers of evidence. It does not assert a single universally optimal bio-asphalt formulation, because a desirable formula depends on the base bitumen grade, traffic spectrum, aggregate chemistry, plant temperature, wet exposure and local supply chain. Instead, it identifies measurable design choices and decision gates [8,9,12,13].

Indonesia is used as an important geographic motivation because it combines major oil-palm processing capacity with extensive tropical road infrastructure, but this does not imply that Indonesian pavement structures or climatic conditions are uniform. Coastal, highland, flood-prone and heavily freighted road sections represent different loading and drainage conditions. Localized surface-temperature histories, rainfall statistics, axle spectra and compaction records must therefore enter the experimental design before the claimed climate benefits can be generalised. Throughout the article, technical readiness is treated as a provisional analytical judgment, not an official technology-readiness certification. The paper advances a field-verifiable pathway in which selected residual inputs enter controlled pilot sections only after chemical reproducibility, multi-distress evidence and life-cycle calculations have survived scrutiny [1,2,6].

Literature Review

Bitumen Chemistry, Colloidal Structure and Ageing

Petroleum bitumen is a complex mixture conventionally interpreted through saturates, aromatics, resins and asphaltenes, although actual molecular architecture varies with crude source and refinery treatment. Asphalt performance reflects not only total chemical composition but the association, mobility and effective interactions of these constituents. Lower-molecular-mass oily components can increase molecular motion, decrease viscosity and shift relaxation behaviour; oxidized species and asphaltene-rich associations can instead produce higher stiffness and brittleness. For that reason, the simple proposition that adding a renewable liquid necessarily creates better asphalt is incomplete. A successful rejuvenator should influence the aged-binder microstructure and recover a useful mechanical balance without creating an excessively lubricated mastic or damaging aggregate adhesion. Chemical differentiation matters particularly for mixtures containing significant RAP and a substantial inventory of oxidized binder [12,15-17]. Reviews of bio-oil and biochar systems also identify composition-dependent phase separation and crystallization phenomena, reinforcing the importance of storage stability and compatibility testing alongside conventional binder rheology.

Short-term thermal conditioning during production and long-term exposure in service transform a binder differently. Oxidation increases carbonyl and sulfoxide-associated signals, while volatilisation and physical hardening alter rheological response. Bio-derived fractions may differ from petroleum components in oxidative reactivity, functional groups, volatility and compatibility with polymer modifiers. Chemically similar viscosity reductions immediately after blending can therefore conceal very different susceptibility to further ageing. Infrared

spectroscopy and compositional fractionation provide useful evidence, but neither is sufficient without time-dependent mechanical testing. Recent assessments of conventional and bio-based ageing stress the need to connect multiple environmental factors with chemistry and rheology, rather than extrapolate single temperature-conditioning protocols to wet, ultraviolet-exposed pavement service [14,18-20].

Functions of Palm Oils, Ash, Fibres, Clinkers and Chars

Palm-derived liquid inputs include fresh vegetable oil, fractions obtained during refining, chemically modified fatty compounds, and spent or contaminated oils when collection and treatment are appropriate. Depending on molecular composition and dosage, these may alter mixing viscosity, improve aged-binder mobility, increase lower-temperature relaxation or act as partial replacements of conventional binder fractions. The term bio-binder is reserved here for a genuine binder-containing liquid formulation; an oil added at a small percentage to a petroleum bitumen is more accurately described as an additive or rejuvenator. Reported studies of palm oil-based compounds demonstrate that chemical formulation is consequential, while reviews of wider bio-asphalt systems show that performance can vary in direction as well as magnitude with feedstock, dosage and preparation [10,21,12,13].

The solid streams operate by other mechanisms. Combustion ashes contribute a mineral or carbon-bearing particulate phase to the mastic, and their effectiveness depends on fineness, mineral composition, loss on ignition, adsorption and compatibility with bitumen. Palm oil clinker may function as aggregate replacement, with porosity and angularity affecting absorption and the mixture skeleton. Fibres can limit binder drainage or provide mechanical bridging if their geometry and distribution are controlled, whereas biochars can stiffen a binder or mastic through surface interactions and a dispersed solid network. Claims made for cementitious pozzolanic reactions should not automatically be imported into asphalt: a hydrophobic binder environment is chemically distinct from water-cement hydration. Performance must be established from actual asphalt tests [11,22-26]. A non-palm experimental investigation found that biochar enhanced selected high-temperature binder properties but impaired some lower-temperature responses, illustrating why improved stiffness is not a comprehensive durability verdict [27].

Rheology and Coupled Pavement Distress

The engineering vocabulary must distinguish binder, mastic and mixture evidence. Penetration, ring-and-ball softening point and rotational viscosity provide useful indices but do not alone determine rutting or fatigue endurance. Dynamic shear rheometry evaluates temperature- and frequency-dependent stiffness and phase angle; multiple stress creep recovery provides a more direct screening response to repeated shear demand, while binder fatigue methods capture accumulated damage under oscillatory loading. At mixture scale, dynamic modulus, wheel tracking, cyclic creep, indirect tensile fatigue and viscoelastic continuum damage characterise components of behaviour that cannot be inferred directly from chemical spectra. A softened rejuvenated binder might improve flexibility but reduce the resistance of the aggregate network to permanent deformation, particularly under high pavement-surface temperatures [12,2,5,28]. Importantly, a 2025 mastic-level study found that volume-equivalent biochar substitution did not universally increase stiffness and could raise water uptake; this non-palm finding reinforces the need to measure filler-specific behaviour rather than assume a generic biochar benefit [29].

Moisture introduces another set of interacting tests. A persistent water film at the binder-mineral aggregate interface can weaken adhesion; trapped water and pore pressure under moving wheels increase stripping and ravelling. Hydrophilic fibres, high-porosity clinker or ash with variable residual carbon may change water storage or interfacial wetting. Consequently, unconditioned Marshall stability or dry indirect tensile strength should not be interpreted as evidence of wet-weather durability. Retained tensile strength, immersion conditioning, Hamburg-type wet wheel tracking, interface adhesion or surface-energy measurements and hydraulic drainage characteristics offer complementary information. They should be interpreted together with binder stiffness, since an overly stiff but well-adhered mixture can still become fatigue-prone, while a flexible mixture may permanently deform in the wet and hot environment [12,30,31,23].

Reclaimed Asphalt, Circularity and Implementation Readiness

RAP mixtures contain aged binder on reclaimed aggregate, but the practical contribution of that binder depends on blending efficiency, temperature, mixing time, rejuvenator diffusivity and possible chemical incompatibility. Nominal RAP percentage therefore does not equal effective recycled binder content. High RAP can conserve virgin aggregate and bitumen, yet poor integration can generate brittle interfaces, localized stiffness and accelerated cracking. Rejuvenators offer a possible route to restore aged-binder flexibility; however, their ability to penetrate and equilibrate throughout reclaimed films remains process-dependent. Recent diffusion, molecular-modelling and blending research provides an important comparator to palm-specific work, but a direct palm-derived RAP dosage cannot be inferred without corresponding performance verification [32,33,16,34,35]. Direct blending experiments with conventional and rejuvenated recycled asphalt further highlight that the timing and mixing route can change effective interaction between fresh and aged binders, an issue that should be tested directly for palm-derived candidates [36].

The circular-economy rationale also requires economic and environmental boundaries. Material diverted from waste management is not automatically low carbon after drying, combustion, grinding, pyrolysis, solvent treatment and long-distance transport. Repeated maintenance, resurfacing and end-of-life recycling can reverse an initial production benefit. Consequential questions include which feedstock is displaced, whether fresh food-grade palm oil is used, whether energy is renewable, what alternative uses the by-product has, and which control mixture provides the reference. The literature on RAP environmental break-even, reclaimed-mixture carbon, and whole-pavement sustainability supports a service-life rather than simple per-tonne comparison. Any provisional technology readiness rating should also distinguish reproducible laboratory data from small field pilots and specifications accepted by a road authority [37,38,6,7,39].

Methods: Critical Qualitative Literature Review

Interpretive Research Design and Unit of Synthesis

This study adopts a critical qualitative literature review, not a systematic literature review, meta-analysis or PRISMA evidence census. Its purpose is explanatory and integrative: it constructs mechanisms linking a palm-derived feedstock, its processing history, its measurable asphalt function, a relevant pavement failure mode and a deployment decision. Studies are selected and discussed to illuminate mechanisms, contrasting findings, and missing knowledge, rather than to estimate an average additive effect from statistically pooled specimens. Interpretive thematic synthesis is well suited because experiments employ dissimilar base binders, particle sizes, mixture gradations, traffic simulations, ageing methods and climatic regimes. Combining these outcomes into a single pooled performance number would imply a comparability not supported by the available studies [8,9,12,13].

The unit of analysis is the material–function–distress pathway. A study receives a distinct evidence label depending on whether it provides direct experimental data for a true oil-palm feedstock in asphalt, laboratory evidence for a specific palm waste but only a limited test battery, analogous results for non-palm oil or biochar, or broader supporting scholarship on tropical risk and life-cycle methods. A direct palm study may still be narrow if its binder formulation is incompletely characterized or no water conditioning is reported. Conversely, an excellent RAP blending study using another oil can clarify mechanism while remaining indirect evidence for palm-based formulations. This hierarchy prevents the subtle but consequential conversion of plausible mechanistic analogy into an unsupported performance guarantee [10,25,40,41,33].

Search Boundaries and Evidence Retrieval

The topical search draws upon journal literature from January 2020 through 14 October 2026, accessed through multidisciplinary publisher databases and scholarly discovery services. Search concepts combine “oil palm,” “palm oil,” “palm oil fuel ash,” “palm oil clinker,” “mesocarp fibre,” “palm kernel shell,” “biochar,” “bitumen,” “asphalt,” “rutting,” “fatigue,” “moisture,” “reclaimed asphalt,” “rejuvenator” and “life cycle”. Citation chaining and targeted searches identify adjacent literature on chemical rejuvenation, ageing, climate impact and recycled asphalt blending. Priority is given to traceable peer-reviewed journal articles with identifiable DOI links. A journal article’s inclusion does not mean that its individual experiments have been independently replicated, nor is every record equally relevant to direct palm performance [8,9,12,42].

The search intentionally spans civil engineering, materials chemistry, transportation science, climate impacts and environmental assessment. It does not include commercial performance claims as scientific evidence, nor does it assume that engineering codes for a different locality can be adopted unchanged for tropical service. Abstract-only evidence may help locate a research theme but should not support detailed quantitative claims without inspecting the study. For the present narrative review, the bibliography contains 51 recent journal items, including palm-focused primary studies, comparator experiments, methodology work and critically relevant reviews. This is a bounded interpretive corpus rather than the result of a declared exhaustive screening procedure; accordingly, no selection flowchart, fabricated database hit count or quantitative inclusion denominator is presented [1,14,13,43].

Coding, Triangulation and Limitations

Each study is conceptually coded for feedstock identity; fresh, residual or post-use status; pre-treatment; particle or molecular descriptors; binder and aggregate baseline; dosage; mixing temperature and duration; ageing condition; observed rheological direction; mixture distress endpoint; moisture conditioning; RAP interaction; and environmental system boundary. Differences are interpreted as potentially causal only where experimental controls, appropriate comparisons and supporting material measurements make such interpretations plausible. The synthesis deliberately registers adverse outcomes, such as improved fatigue alongside weaker rutting resistance, or improved stiffness at the price of embrittlement. Apparent contradictions may reflect feedstock heterogeneity, binder grade, conditioning protocol or the scale at which a response was measured rather than flawed research [44-46,30].

Three triangulation questions guide each conclusion. First, does a reported binder-level effect remain coherent when expressed at mastic and compacted-mixture scale? Second, does the direction of improvement survive realistic short- and long-term ageing and wet conditioning? Third, is the effect likely to remain relevant after plant production, traffic, drainage and maintenance are included? When studies provide no direct field observations, the corresponding readiness assessment is explicitly provisional. This design has limitations: publication bias, inconsistent material labels, incomplete open-access data and the limited availability of tropical in-service evaluations prevent definitive regional recommendations. Rather than conceal those restrictions, the discussion identifies which measurements and demonstrations would make future causal and economic judgments stronger [37,47,39,14].

Results: Thematic Findings

Palm-Derived Oils, Fatty Compounds and the Balance Between Flow and Cohesion

The first thematic finding is that “rejuvenation” and “substitution” describe distinct performance propositions. As a rejuvenator, a palm-derived fluid is intended to rebalance an oxidized binder or lower processing viscosity while preserving enough high-temperature shear resistance. As a partial substitute for a petroleum binder, the same fluid also changes the overall molecular-association structure and the relative proportions of functional groups. The palm oil additive research of Uchoa and co-workers offers direct chemical and rheological evidence for modified palm components, while the tire-pyrolysis and bio-asphalt formulations investigated by Al-Sabaeei and colleagues indicate the importance of mixed feedstock and formulation effects. Such results justify careful laboratory screening; they do not establish that crude oil and every derivative are mutually replaceable or that a favourable single binder index equals pavement-level success [10,21,8].

The second finding is that reduced viscosity cannot be treated as a universal benefit in a hot tropical climate. Improved workability can enhance aggregate coating, enable somewhat lower production temperatures or assist aged-binder dispersion,

but the same increase in molecular mobility may intensify permanent deformation if the formulation weakens the effective binder skeleton. Reviews covering a wide range of bio-oils repeatedly report this workability–rutting tension. Analogous experiments with waste cooking oil, chemically functionalized lipids and tyre-rubber blends demonstrate avenues for chemical tuning and mechanical compensation; nevertheless, differences in fatty acid profile and processing prevent direct conversion of those test outcomes into a palm-oil recipe. The desired objective is therefore a dosage window that meets rutting, fatigue and wet-adhesion constraints simultaneously, not a maximum feasible proportion of renewable liquid [40,18,48,49,12,13].

Additional distinctions arise from durability and chemical processing. Transesterification of used cooking oil has been investigated as a rejuvenator, while controlled chemical modification can yield products with more favourable long-term behaviour than an untreated feedstock. Investigations of individual chemical fractions show that nominally similar waste oils can age differently; studies of bio-oils in aged polymer-modified binders reinforce the need to examine compatibility with residual elastomer networks. These papers are comparator evidence, not a basis for claiming identical effects from palm-derived residues. Fresh vegetable oil should also be scrutinized for its alternative value in food and industry; lower-value residue fractions warrant priority only when contamination, acidity, water content and batch-to-batch chemistry can be controlled. For tropical pavement use, secondary ageing and wet mixture strength are indispensable endpoints [46,40,19,20,43,41].

POFA, Boiler Ash and the Mineral Mastic Pathway

The reviewed ash studies indicate a separate physical route to performance. Palm oil fuel ash (POFA) and boiler ash can occupy space otherwise filled by mineral fines and potentially alter the mechanical response of the mastic. Ash fineness affects surface area, binder demand and mixture compactability, while residual unburned carbon can adsorb organic constituents and disrupt a nominal dosage calculated only by mass. Usman and colleagues investigated POFA in cold-mix dense-graded bituminous material, supporting a role for this residue as a mixture constituent; Rosyidi and colleagues characterized the chemistry, thermal features and physical properties of boiler-ash-modified binders. These studies make feedstock processing a design parameter rather than a footnote: drying, screening and grinding influence both binder interaction and reproducibility [23,50,9].

The principal risk is an erroneous transfer from cement chemistry. POFA is often discussed as a silica-bearing supplementary cementitious material, but an asphalt mixture lacks the water-rich cement hydration environment through which classic pozzolanic strength develops. In bituminous mastics, the dominant accessible mechanisms are particle packing, interparticle interactions, morphology-dependent stiffening, surface adsorption and binder–filler affinity. An ash that performs well in a mortar cannot thereby be presumed to improve asphalt moisture durability or fatigue. High loss on ignition, variable combustion temperature and nonuniform grain shape can cause inconsistent effects even when bulk silica content appears attractive. Future asphalt-oriented characterisation should report particle-size distribution, specific surface area, density, carbon content, soluble salts and water susceptibility alongside composition, and should compare equal effective volume fractions as well as equal mass dosages [23,50,51,30].

Hybrid combinations complicate the mastic picture further. Waste-containing hybrid binder experiments, including systems with palm-derived mineral residues, suggest that a filler or stiffening phase may counterbalance some effects of softer or otherwise modified binders. Yet a satisfactory rotational viscosity at mixing temperature does not exclude aggregate adhesion losses or brittle fatigue under long-term conditioning. Changes in the resilient modulus of a mixture can also result from altered air voids or absorbed binder rather than inherently beneficial chemistry. For engineering specification, ash trials should distinguish the total added solid from the effective active mastic volume, maintain target volumetrics and document moisture conditioning. Conditional suitability is plausible for selected, reproducibly processed ashes, while their diverse feedstock histories prevent a universal designation of POFA as a high-performance asphalt modifier [45,50,51,12].

Palm Biochar, Shell and Clinker: Carbonaceous Versus Aggregate Mechanisms

Biochar provides a compelling but still early-stage research pathway. Pyrolyzed mesocarp fibre and palm kernel shell yield carbonaceous particles with surfaces and pores that differ from raw fibres or ordinary mineral filler. Direct palm-derived biochar research by Chaves-Pabón and collaborators and Rondón-Quintana and collaborators reports asphalt-mixture performance tests sufficiently specific to motivate deeper evaluation. The apparent opportunity is to adjust binder–filler interaction and high-temperature stiffness without relying solely on a liquid rejuvenator. Yet the effective interaction depends on pyrolysis temperature, char ash fraction, pore accessibility, particle fineness and the dispersion process. Non-palm metal-rich biochar studies show additional mechanisms, including volatile-emission effects, but their chemistry should be treated as indirect rather than palm-specific evidence [25,26,39,30].

A char's stiffening potential is not synonymous with greater service life. Where stiffness improves rutting control, excessive dosage may increase local stress concentration, lower fatigue endurance, inhibit stress relaxation or alter water access at poorly wetted interfaces. The performance direction is also influenced by base binder: a soft binder may benefit from a char fraction that causes brittleness in an already stiff aged binder. This points toward function-specific acceptance criteria combining multiple stress creep recovery or other binder deformation metrics with cyclic fatigue and conditioned wet tracking. Char production energy must be measured rather than assumed to be negligible; pyrolysis yield, heat recovery and transport distances affect the environmental result. The current palm-char literature is best regarded as laboratory proof of technical plausibility rather than field demonstration across representative Indonesian wet seasons [25,26,39,6]. Complementary studies of biochar-modified binder and mastic have reported different stiffness responses across feedstocks and specimen scales, and some have identified water-sorption and ageing-related trade-offs; these outcomes caution against transferring generic biochar claims to palm fibre or shell chars [27,29].

Palm oil clinker and shell fragments should be interpreted differently. Clinker behaves substantially as an aggregate substitute, so porosity, angularity, crushing resistance and absorption influence the load-bearing mineral skeleton. Experimental stone mastic asphalt studies by Babalghaith and colleagues indicate that POC incorporation can be technically evaluated at multiple aggregate-replacement levels; another Yaro study explores fine-clinker substitution within asphaltic concrete. Tagbor and colleagues evaluated palm kernel shells in mixtures also containing plastic, which means a performance improvement cannot automatically be attributed exclusively to the shells. A workable substitution percentage for one mineral gradation, traffic classification or binder content may fail elsewhere. Reported engineering properties should therefore be normalised to gradation, void structure, absorbed binder and local aggregate specifications, followed by polishing, abrasion and wet strength checks as relevant [11,22,44,52].

Palm Fibres and Reinforcement without Assuming Universal Crack Resistance

Mesocarp fibres and other palm-industry fibres are often discussed as low-cost reinforcement, but their most reliable mechanistic candidate role can be mixture stabilisation. In stone mastic asphalt, discrete fibres help control binder draindown and influence the distribution of the rich mortar phase. The study by Yaro and colleagues explicitly compared traditional and sequential mixing processes, underscoring that mixing route and fibre dispersion are not secondary variables. Fibre dimensions, surface moisture, pre-treatment, concentration and aggregate interaction all influence whether the reinforcement disperses or forms clusters. If fibres agglomerate, the nominal reinforcement can create vulnerable zones of insufficient coating, excess voids or inconsistent compaction. A properly measured benefit is therefore conditional on uniform mixing and an appropriate mastic design [24,11,9].

Crack bridging is a different and stronger performance claim than reduction in draindown. Establishing crack-resistance improvement requires evidence from fatigue testing under appropriate strain or stress control, or from mixture fracture methods that capture crack initiation and propagation. Increased Marshall stability is not an adequate surrogate. A high-fibre mixture may exhibit enhanced resistance to one deformation mechanism but a poorer response to moisture or repeated damage, especially if porous natural fibres absorb water. Fibre surface preparation and mixing sequence should be evaluated against alternatives such as mineral fibre or cellulose-based commercial stabilizers using equivalent volumetric design. When fibres are combined with softer rejuvenating oils or stiffening char, factorial designs are preferable to attributing the composite result to one selected ingredient [24,5,17].

The most useful innovation may be in hybrid systems rather than single-additive optimisation. A properly selected low-viscosity residual lipid could aid aged-binder distribution while a fine char or mineral phase counteracts hot-temperature flow; fibres could limit draindown in gap-graded mixtures. However, such a balance is a design hypothesis, not a validated general solution. Each component influences binder availability, wetting and effective mastic volume, and interactions may be antagonistic rather than additive. Laboratory trials should therefore include a neat-bitumen control, individual-component controls and mixture-level hybrid specimens prepared under identical compaction and conditioning procedures. Response-surface experiments and predictive models developed for palm mill wastes are useful for screening but require external validation and meaningful mechanistic predictors before being used as specification substitutes [45,51,53,24]. Comparative bio-oil/biochar research reports potential compatibility benefits but also raises the possibility of phase separation at unsuitable compositions, so hybrid blends should include a defined storage-stability evaluation before mixture-scale validation [54].

Tropical Distress: Rutting, Fatigue and Moisture Under Combined Exposure

Rutting is a central concern in tropical paving because bituminous binders tend to become more compliant as temperature rises while heavy axles apply repeated shear forces. A liquid rejuvenator could be acceptable in a moderate service climate but unacceptable when surface temperature and sustained traffic are high. Conversely, stiffening fillers, clinker skeletons or fine char may improve resistance to permanent deformation when used within a suitable mixture design. The relevant experiment is not a single binder softening point: it is a comparative wheel-tracking and rheological programme covering expected upper temperature percentiles, repeated stress and realistic aggregate/void conditions. Regional climate studies show that the rutting implications of warming vary by climatic setting, making the local design temperature and loading history indispensable [2,30,51,53].

Fatigue cannot be represented simply as the inverse of rutting. Binder relaxation, mixture modulus, loading mode, ageing state, air voids and pavement layer thickness all influence crack accumulation. A stronger or more elastic binder response may defer damage at one strain level yet transmit higher stresses in another structural configuration. Oxidative ageing further changes damage behaviour, and continuum-damage methods provide more informative descriptions than a solitary unconditioned strength measurement. In comparing oil-derived additives with biochar or ash, a fair experiment should test the same target air voids and apply comparable cyclic histories before interpreting durability. Both binder fatigue indices and mixture-based crack development matter; a chemically promising rejuvenator should not pass selection unless its recovered flexibility survives long-term conditioning and its hot-temperature rutting remains acceptable [5,17,18,20].

Rainfall creates an equally essential gate. Water ingress depends on permeability, fissures, surface drainage, aggregate mineralogy and binder-film continuity. Additives that alter wetting or sorption can modify stripping even when the initial dry mixture appears strong. The comparison literature on waste oil rejuvenation illustrates a recurring need to assess moisture sensitivity and the possibility that certain oil functions undermine aggregate adhesion. High-porosity clinker, wet fibres and some ashes introduce further pathways of water retention, while finely distributed biochar can alter the interface in ways that depend on its surface chemistry. No single moisture index can fully represent hydro-mechanical pavement performance.

A tropical qualification programme should combine laboratory conditioning, wet wheel tracking, aggregate-specific adhesion assessment and field drainage observations, especially on flood-prone freight corridors [46,12,31,23,25]. In recycled-mixture research, differences in waste-oil dose and mixing sequence have changed the reported resistance to wet conditioning, underscoring the need for binder-and-aggregate-specific controls in tropical palm-derived asphalt experiments [55].

Figure 1 translates these findings into a material-function-performance pathway. The diagram avoids treating a common palm origin as proof of interchangeable chemical behaviour and instead makes the engineering function an explicit mediator of outcomes. For example, oils enter through the binder mobility pathway, ashes through mastic packing, and clinker through aggregate structure; each consequently requires a different acceptance test and produces a different class of potential failure. The figure is a conceptual decision aid rather than a graph of observed effect sizes. Its three columns also explain why manufacturer assertions that one additive increases "asphalt strength" are not adequate: the relevant property must be named, measured at the appropriate structural scale and interpreted in conjunction with its opposing risk [8,9,12].

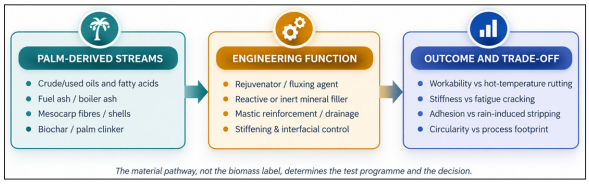


Figure 1: Palm feedstock-to-pavement function and trade-off pathways (original conceptual synthesis; no empirical effect sizes)

In Figure 1, the central engineering-function column acts as a causal discipline. The same residual palm material may require different processing to operate as a fine filler, a shell aggregate or a carbonaceous modifier, and processing conditions can dominate nominal feedstock identity. The right-hand column highlights explicit counterfactuals: improved workability should be tested against heat-induced shear flow, higher stiffness against aged fatigue response, and nominal circularity against processing emissions. This visual taxonomy provides the organizing logic for the material-selection matrix introduced in the discussion. It also makes clear that engineering claims should be specific to application—surface course, binder course or cold-mix maintenance—and to the service environment rather than generalised to all pavements [9,13,30].

RAP Circularity and the Distinction Between Rejuvenation and Blending

A dual-circular scenario would combine recovered asphalt with a palm-derived residual rejuvenator. The theoretical attraction is simultaneous reduction of virgin bitumen demand and valorization of a low-value liquid stream. But the most critical hidden variable is effective blending. A fresh liquid may lower the viscosity of newly added binder while only partially interacting with the aged film coating RAP particles; this can produce spatially heterogeneous properties and misleading average rheological measurements. Recent studies of diffusion, fusion, dynamic shear blending indices and molecular-level RAP rejuvenation show why the distinction between nominal RAP ratio and activated recycled binder is consequential. A palm-specific high-RAP mixture should therefore quantify mixing energy, sequence, temperature and effective blend formation rather than assume uniform molecular equilibration [32,33,16,34,35].

The waste cooking oil literature demonstrates options without confirming a palm-specific result. Researchers have compared waste oil with aged asphalt, chemically modified recovered oils, rubber-modified rejuvenators, polymer-modified mixtures and UV-aged binder. These studies identify controllable chemical variables and show that a recycled oil's manufacturing history can shape both early workability and secondary ageing. Capitão and collaborators investigated hot and warm mixtures incorporating high RAP with waste cooking oil; other work examines combined SBS modification and rejuvenation or epoxy-assisted high-RAP mixtures. Such evidence suggests that a palm-derived candidate deserves comparative experimental testing, but its fatty-acid distribution, contaminant content and chemical stability must be characterized independently. High-RAP palm trials should include a commercial rejuvenator benchmark and a RAP-only control [46, 18,48,49,20,47,37]. Controlled recycled-mixture experiments show that mixing method, rejuvenator dosage and RAP content can alter moisture resistance as well as binder activation; these results are relevant test-design comparators but not direct evidence for palm residual oils [55,56].

The most demanding RAP test is long-term service equivalence, not the immediate restoration of a target penetration value. Rejuvenated binder can re-harden in service, and a formulation that passes early fatigue testing may become brittle after ultraviolet, oxygen and water exposure. The life-cycle result is equally sensitive to the maintenance schedule, because extra repair cycles can erase saved virgin inputs. Comparative investigations of waste engine oil and cooking oil, soybean-based agents, chemical fractions and broader RAP recycling illustrate the diversity of available options; no method offers a universal guarantee under all aggregate and climate conditions. Direct palm trials should measure secondary ageing and moisture resistance, characterise recycled content after construction and account for future recyclability of the mixed pavement material [43,19,41,15,31,57]. A comparative investigation of low-viscosity binders and recovered cooking oils likewise found formulation-dependent secondary ageing in RAP systems, indicating that initial softening alone is an inadequate proxy for a stable service-life benefit [58].

Environmental and Cost Implications of a Residue-Based Strategy

Palm residues offer a potentially credible circular feedstock when they are already generated locally and have limited alternative value. Yet the correct environmental comparison is not "biomass versus petroleum" in the abstract. Fresh food-grade palm oil has potential economic and land-use opportunity costs, while waste streams can demand drying, sorting or contamination control. Biochar may require substantial heat input; mineral ash may require grinding and dust management; clinker can change haulage mass and compaction energy. A cradle-to-maintenance assessment should include feedstock allocation or substitution, collection, pre-treatment, emissions from mixture production,

transportation, construction, rehabilitation frequency and end-of-life fate. Studies of recycled asphalt LCA and pavement innovation identify the importance of selecting consistent functional units and sensitivity ranges [37,38,6,7].

Economic performance similarly depends on durability. A lower-price additive that increases binder demand, requires more testing or shortens resurfacing intervals may not reduce whole-life cost. The appropriate comparator should deliver the same functional pavement duty, not simply the same tonne of mixture. Environmental hotspot analyses of RAP and rejuvenators illustrate that transport and process choices can alter the break-even result; carbon studies of modified recycled mixtures highlight the distinction between material inputs and actual cradle-to-construction impact. Maintenance frequency is especially consequential on heavily trafficked routes, where lane closures and detours may dominate social disruption. In a tropical pilot, life-cycle cost should therefore include acquisition, process yield, quality testing, installation, monitoring, scheduled preservation, corrective repairs and an uncertainty allowance for unproven material service life [37,38,6,7].

Figure 2 expresses the tropical exposure domain as a combined rather than sequential challenge. Heat and axle loading, wetting and hydraulic effects, and field production variability jointly feed into a multi-distress acceptance gate. The graphic is intentionally qualitative: it does not assume that a tropical surface always reaches one universal temperature, that all Indonesian rainfall is equivalent or that every aggregate has the same stripping propensity. Its purpose is to require local inputs and to prevent a test programme optimized only for rutting from overlooking field conditions that could reverse a favourable laboratory ranking. The framework can be adapted to surface courses, binder courses, porous asphalt and cold-mix repair, provided each application receives its own functional performance thresholds [2,1,30]. This framing is also consistent with the broader climate-adaptation literature, which treats temperature-sensitive material properties and flood-driven structural deterioration as interacting, not interchangeable, pavement challenges [4].

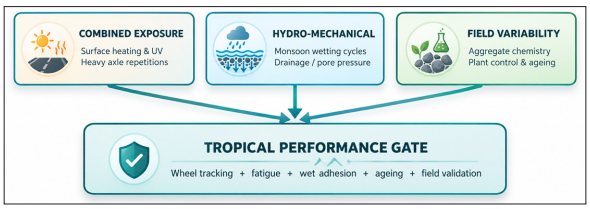


Figure 2: Coupled tropical exposure framework for hot-wet pavements (original analytical schematic)

The bottom gate of Figure 2 gives equal conceptual standing to performance after ageing and performance after wet conditioning. This is particularly important for additives that alter viscosity or aggregate surface adsorption. A mixture with impressive dry wheel-tracking resistance can still be unsuitable if its interfacial adhesion collapses after water conditioning; likewise, an initially ductile rejuvenated binder can lose that benefit during oxidation. Realistic conditioning protocols should be derived from measured local climates and checked against field-core behaviour as pilot data accumulate. The evidence base currently favours cautious mechanistic screening and monitored demonstration, rather than a blanket conclusion that palm-based pavement inputs already possess proven tropical resilience [14,1,46,25].

Discussion and Analysis

Reconciling Binder Chemistry with whole-Mixture Durability

The cross-study synthesis yields an asymmetric conclusion: there is meaningful evidence of experimental feasibility, but less evidence of performance equivalence in service. It is plausible that liquids can restore molecular mobility, chars and fillers can stiffen selected binder systems, and fibres and clinker can influence mixture structure. It does not follow that these interventions can be ranked by renewable content or even by a common binder rheology value. Binder formulation, mastic composition and aggregate mineralogy are nested design levels with interactions that can alter the sign of a result. An oil whose rejuvenation effect is beneficial for stiff RAP could make virgin bitumen too soft; a char that compensates for oil-induced flow might cause fatigue brittleness after oxidation. The design problem is multiobjective and conditional, not additive-benefit maximization [8,10,25,12,13].

Evidence strength varies sharply across the pathways. Direct laboratory studies of mesocarp-fibre biochar, shell-derived biochar, palm oil clinker, fibres and ashes show that these material classes have genuine pavement research foundations. However, early performance reports frequently involve one source, one binder family, selected dosages and finite conditioning histories. They cannot provide a robust general-purpose specification for heterogeneous commercial feedstocks. Broader research on soy agents, babassu oil and other vegetal oils helps identify rheological questions, but babassu is not the oil palm species of the industrial value chain assessed here. A scientifically defensible comparison labels such papers as non-palm analogues; even apparently similar acids or viscosity profiles do not establish equal long-term moisture adhesion or chemical ageing for Elaeis guineensis residues [11,22,24,-26,57,59].

The engineering response is to replace a single optimum-content chart with a Pareto decision surface. Researchers should plot rutting resistance, conditioned fatigue life, wet adhesion, production viscosity, emissions and whole-life cost at multiple dosages and ageing states. A blend that is best on one response but violates a critical threshold on another is not feasible, regardless of favourable composite scoring. The governing thresholds should be drawn from the road agency's accepted mix specification, locally calibrated climate and expected traffic class. For example, a hot-climate surface mixture might impose strict upper limits on permanent deformation and wet stripping, whereas a low-volume maintenance mix may prioritise compactability and moisture resistance under cooler placement conditions. Each application requires function-specific controls and an explicit no-worse-than-baseline test [51,53,12,2,30]. Experimental work on recycled asphalt demonstrates that the optimum rejuvenator dose depends on the blend and the mechanical endpoint, strengthening the case for conditional performance limits rather than a universal dosage recommendation [56,58].

Material-selection Matrix and Provisional Technology-Readiness Assessment

Table 1 synthesizes material suitability by linking a specific palm-derived stream to its most plausible engineering role, potential benefit, critical failure mode and provisional readiness range. It is deliberately not a leaderboard of superior products. Values are author judgments using a broad one-to-nine technology-readiness concept: low numbers indicate laboratory formulation or proof of principle, while higher values would require increasingly credible relevant-environment and operational demonstrations. The stated ranges represent approximate application-specific readiness based on the literature reviewed; they are not an independently audited TRL instrument and should not be compared numerically across jurisdictions without calibration. Particularly low ranges for palm-derived rejuvenator-plus-RAP systems reflect limited direct coupled-distress field validation rather than an assertion that their chemistry is infeasible [9,10,11,25,26,37].

Table 1: provisional Functional Selection of Palm-Derived Pavement Inputs. TRL Ranges are Author-Assessed, not Certified

Material	Pavement role	Plausible benefit	Key uncertainty/risk	Indicative TRL
Spent/processed palm-derived lipids	Rejuvenator / warm-mix flux	Mixing workability; restore aged binder mobility	Rutting, volatilisation, moisture adhesion	2-4; formulation-specific
Functionalised fatty compounds	Chemically tuned rejuvenator	Control mobility or ageing relative to raw oil	Cost, chemical residues, secondary ageing	2-3; mainly analogue evidence
Palm oil fuel ash / boiler ash	Filler / mastic mineral phase	Mineral substitution and mastic stiffness	Carbon, moisture, particle variability	3-5; lab mixtures
Palm mesocarp fibre	Stabilising reinforcement	Binder draindown control; mechanical bridging	Dispersion and fibre moisture uptake	3-5; lab mixtures
Palm kernel shell biochar	Micro-filler / stiffening modifier	Enhanced hot stability in selected mixtures	Brittleness; production-energy burden	2-4; direct recent lab
Palm mesocarp fibre biochar	Carbonaceous reinforcement	Modulate rheology and mixture deformation	Excess stiffness; variability, moisture	2-4; direct recent lab
Palm oil clinker	Fine/coarse aggregate replacement	Circular aggregate and skeleton effects	Absorption, gradation, compaction	3-5; lab mixtures
Palm shell fragments	Aggregate substitute	Partial reduction in virgin aggregate use	Weakness, abrasion, uncontrolled pores	2-4; experimental mixtures
RAP plus palm-derived rejuvenator	Integrated circular mixture	Reduce virgin bitumen and aggregate demand	Incomplete blending; re-ageing; rutting	2-3; direct field proof limited

Table 1 should be read as a screening decision rather than a fixed ranking. For example, processed palm oils may be most compelling when applied to aged RAP binder under a deliberately constrained dosage, while ash and char may be candidates to adjust mastic or shear response in a warm-weather design. Fibres and clinker have different functional pathways and should be evaluated at mixture scale. No row presumes that residual biomass is chemically consistent merely because it comes from the same crop. The table also separates the useful "potential benefit" from the unmeasured "technology readiness": successful pilot construction, years of distress monitoring and transferable procurement quality control would be required before a laboratory candidate could be treated as a mature tropical highway material [8,9,24-26,45].

A practical feedstock decision also needs an exclusion filter. Unknown contamination, excessive source variability, poor drying stability, unaccounted energy input or unresolvable supply chain traceability can disqualify a candidate even where its laboratory rutting performance appears attractive. A road authority should demand a declaration of the material's generation point, post-processing steps and material safety profile, together with samples representing seasonal plant operation. Controls for food-grade diversion and competing land use are especially important for claims framed as circular rather than merely renewable. Such requirements help avoid a perverse outcome in which an asphalt project creates new demand for virgin edible oil while overlooking by-products already available near asphalt mixing facilities [37,38,6,7].

A specification-Oriented Tropical Validation Protocol

Table 2 presents a minimum evidence architecture for qualification. It is deliberately a set of measurement categories and decision purposes rather than invented numerical pass–fail limits; authoritative thresholds vary with aggregate type, binder grade, pavement structure and road-agency standards. The first gate is source characterization, including binder compatibility or particulate fineness, water content, residual carbon, fibre length, pyrolysis history or clinker absorption as appropriate. The second gate addresses processing repeatability and short-term ageing. A third gate covers the coupled rutting–fatigue–moisture performance of properly designed mixtures. A fourth gate monitors initial road sections against nearby control sections through wet and dry seasons. Only after those stages should a jurisdiction develop provisional acceptance bands for a given feedstock class [14,23-25,50,].

Table 2: Proposed Tropical Qualification Matrix Linking Laboratory and Field Validation to Explicit Engineering Decisions

Qualification concern	Indicative measurements	Decision to support
Hot deformation	RTFO-aged DSR, MSCR, temperature-dependent wheel tracking	Avoid softer binder or excess rut depth at locally realistic high surface temperatures
Rainfall & stripping	Conditioned tensile-strength ratio, Hamburg wet wheel tracking, surface-energy/adhesion	Track conditioned rut growth and substrate-specific wet bond deterioration
Ageing & fatigue	PAV/UV/wet-aged FTIR and rheology; LAS or S-VECD mixture fatigue	Detect oxidation, embrittlement, microcracks and recovery of recycled binder
Process consistency	Moisture, PSD, ash carbon, fibre length, char pyrolysis record, plant audits	Require supply-lot QC and repeatability of blended material
Road performance	Paired field sections, cores, IRI/rutting/crack maps, wet-season monitoring	Confirm laboratory ranking with at least multiple wet/dry cycles
Circular claim	Cradle-to-maintenance LCA/LCC with counterfactual and sensitivity tests	Count collection and processing energy, haulage, avoided landfill and repair intervals

A particularly important protocol improvement is to sequence conditioning realistically. For a candidate rejuvenator, binder rheology should be measured before and after short-term and long-term ageing; wet-conditioned mixtures should be tested against aged and unaged controls. For clinker and porous ashes, absorption and compacted mixture voids should be tracked to avoid confusing binder shortage with a chemical incompatibility. For char, laboratory tests should vary its fineness and dispersion method while recording thermal processing energy. Fibres should be tested across placement and compaction methods to expose segregation. The intent is not to prescribe one universal sequence, but to make the critical coupling explicit: heat influences stiffness, water influences adhesion, traffic accumulates damage and plant conditions determine whether the laboratory material can actually be reproduced [23-26,5,14].

Performance indicators must be interpreted by scale. DSR and FTIR can show that a particular binder blend has changed, but an asphalt mixture's stone skeleton, filler volume and air voids often dominate the direction of rutting or moisture damage. Marshall stability and indirect tensile strength can flag obvious weaknesses but do not replace repeated-load or fracture characterisation. Mixture wheel tracking, dynamic modulus and fatigue testing should therefore accompany the binder-level series, with controlled gradation and binder content. Where moisture is central, wet wheel tracking should be supplemented by retained tensile strength or aggregate–binder adhesion methods. Standards should require multiple replicate batches and explicitly report test temperatures, conditioning history and specimen volumetrics; otherwise, apparently reproducible "optimum" percentages may reflect unreported design differences [12,2,5,30,17].

Figure 3 summarizes the qualification logic as progressive gates. Each stage can reject or redirect an attractive but inadequate formulation, including a nominally circular feedstock with high drying energy or a low-viscosity rejuvenator that fails hot-temperature deformation criteria. The graphic also communicates an asymmetry in evidence costs: fundamental characterization is relatively inexpensive compared with constructing and monitoring a field demonstration, so early gates should screen out poorly defined feedstocks before road-user risk is incurred. The final stage requires comparison with conventional controls and a maintenance-aware carbon and cost analysis. A material should advance only when the relevant evidence demonstrates suitability for the intended layer and site, not when an arbitrary percentage of palm content has been reached [37,6,7,14].

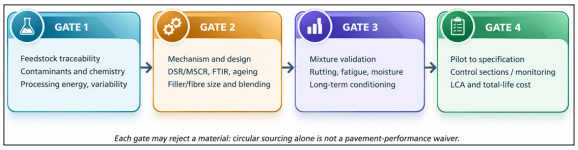


Figure 3: Four staged evidence and specification gates for palm-derived pavement materials (original roadmap)

As Figure 3 emphasises, a pilot is not merely a ceremonial final check. It is a scientific validation of whether laboratory mixtures survive changes in plant mixing, material storage, compaction, construction humidity and the first rainy seasons. The pilot design should pair modified and unmodified sections under comparable traffic and drainage, collect density and binder content records, monitor rut depth and cracking, and retain archived source samples. A suitable programme should pre-register practical intervention triggers and data governance arrangements so that adverse performance cannot simply be explained away after the fact. The results should feed into material-specific procurement tolerances, including accepted feedstock variability and the allowed processing window, rather than produce a broad endorsement of every palm-derived additive [9,25,26,1].

Circular Road Engineering, Policy and Research Priorities

For Indonesia and other producing regions, the strongest strategic argument is an integrated circular-road demonstration rather than a rapid nationwide binder substitution target. Local oil mills, biochar processors, asphalt producers, universities and road agencies could jointly qualify defined residual streams under traceable production lots. A side-by-side research design would compare at least a conventional control, a RAP control, a palm-residue candidate and an established commercial modifier or rejuvenator. Results should be disaggregated by source material, mixture type, binder grade and climate exposure. An experimental framework of this kind may reveal that some residues are best used as aggregate alternatives and others as rejuvenators, avoiding the inefficient requirement that every waste stream become a liquid binder substitute [9,11,24,25,49].

The most urgent scientific gaps concern combined ageing and moisture, reproducibility of palm-derived chemistry and solids processing, and actual performance on heavily trafficked wet tropical roads. Needed studies include chemical fractionation and oxidative stability of low-value palm oils; binder-to-mixture comparison under comparable stress and conditioning; field-representative wet wheel tracking of char and ash mixtures; long-term RAP binder blending verification; and multi-season instrumented trials. Additional work should test whether changes in asphalt performance are consistent across distinct local aggregates, rather than assuming a favourable interface observed with one stone source generalizes nationally. Model-based approaches can optimize laboratory exploration, but their predictors and training data should be physically meaningful and validated independently before optimisation results are transferred to production [45,53,20,32,33,14].

Policy development should privilege open reporting templates and conditional approval. Each qualification dossier could disclose feedstock source, lot variations, composition, processing energy, mixture design, binder ageing, distress-specific results, environmental functional unit, uncertainty and negative findings. Public agencies would then be able to compare competing alternatives without relying on nonstandard trade names or incomplete "green asphalt" labels. Where data are immature, supervised experimental works are preferable to high-volume procurement commitments. Economic assessment must compare costs per lane-kilometre-year of satisfactory service rather than per tonne alone, with maintenance timing, vehicle delays, carbon accounting and uncertainty included. This approach aligns with the broader argument that roadway adaptation and circularity must be evaluated as interacting infrastructure-system objectives rather than as independent material claims [37,2,38,1,6,7].

Finally, there are limits to what this review can conclude. It does not constitute a formal life-cycle inventory for Indonesian mills, does not report a new national pavement-temperature series and does not verify the operational TRL of a named supplier. The material matrix therefore represents a hypothesis-organizing synthesis, not certification. Differences in test methods, nonrepresentative climate conditioning, incomplete chemical data and the scarcity of multi-year field studies prevent statistically defensible estimates of average palm additive benefit. The advantage of a critical qualitative review is precisely that it can expose those limitations, reconcile apparently conflicting laboratory outcomes and specify a measurable route to stronger evidence. The central research output is a rigorous question for each candidate: what is the functional benefit, what competing distress might worsen, and which observation would disprove readiness? [8,9,12,13,1,14].

Conclusions and Recommendations

Integrated Synthesis

Palm-derived materials are not one technological class. Oils and modified fatty compounds principally influence molecular mobility and rejuvenation; ashes change mastic mineral structure; fibres stabilize and reinforce certain mixtures; clinker contributes an aggregate skeleton; and biochars add a potentially stiffening carbonaceous phase. Direct laboratory research supports the technical feasibility of selected applications, yet the hot-wet loading and long-term durability of tropical pavements remain insufficiently demonstrated for blanket claims of performance equivalence. The principal engineering implication is a trade-off framework: workability must not be purchased through excessive rutting, stiffening must not create brittle fatigue, and apparent dry strength must not obscure wet stripping. Composition and treatment history have to be recorded before any comparison is meaningful.

Reclaimed asphalt offers a compelling second circular loop, especially when low-value palm-derived fractions could supplement aged-binder recovery. Nonetheless, effective aged-binder blending, re-ageing, wet adhesion and plant-scale reproducibility must be demonstrated experimentally. The evidence from other waste vegetable oils and biochars informs hypotheses about chemistry and process design but cannot substitute for palm-specific validation. Similarly, an environmental advantage requires more than a renewable label: cradle-to-maintenance emissions, transport and processing demand, alternative feedstock uses, durability and life-cycle costs must be represented. The proposed material-selection matrix is therefore an explicitly provisional starting point for research prioritisation and engineering qualification, not an endorsement of a commercial road-binder grade.

Research, Practice and Policy Recommendations

Research groups should prioritise laboratory matrices that hold air voids, binder grade and gradation constant while changing feedstock dose, processing and ageing; measure hot-temperature repeated-load resistance alongside fatigue and moisture sensitivity; and establish direct palm–RAP comparative trials against commercial rejuvenators. Oil mills and modifier processors should develop supply-lot documentation for ash chemistry, char pyrolysis parameters, residual-oil condition and fibre geometry. Road agencies should require phased technical demonstration and transparent control sections in representative hot, wet and heavily loaded corridors. Acceptance should follow pre-declared functional performance limits and monitored evidence, with unsuitable formulations rejected or restricted to lower-risk applications rather than generalised to all road classes.

Future reviews will benefit from shared tropical exposure datasets, longer monitored pavement records, comparable reporting on life-cycle impacts and more transparent disclosure of unfavourable results. A credible circular road strategy should target waste avoidance and useful service life at once. The most promising near-term route is not indiscriminate replacement of petroleum bitumen but precise matching of characterized local residues to a distinct binder, mastic or aggregate function, followed by laboratory-to-field validation. Only when traffic resilience, moisture durability, repeatable manufacture and full-system cost and emissions can be demonstrated together should palm-derived bio-asphalt advance from a sustainable-material hypothesis to an engineering specification.

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