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From Variable Palm Residues to Certifiable Low-Carbon Concrete: A Critical Review of POFA and Biochar Processing, Microstructure, Durability, and Performance-Based Standardisation

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ABSTRACT

Palm oil fuel ash (POFA) and palm-biomass biochar have attracted interest as lower-carbon concrete constituents, yet material variability continues to impede confident engineering adoption. This critical qualitative literature review shifts attention from cement-replacement feasibility to the causal relationships among residue origin, processing, cement microstructure, exposure-dependent durability and qualification. Evidence from 2020–2025 journal research is interpreted across mineral-ash treatment, biochar pyrolysis, hydration kinetics, strength and deformation, chloride transport, carbonation, reinforcement corrosion and life-cycle performance. POFA primarily offers potentially reactive siliceous and packing functions; biochar introduces distinct porosity, moisture-management and carbon-retention functions. Neither has universally beneficial effects, and results from non-palm biochars should not be interpreted as direct validation of palm-residue formulations. The review proposes five qualification gates spanning source traceability and environmental safety, processing control, role-specific screening, exposure-based concrete verification and independently monitored pilot deployment. It also outlines an Indonesian tropical/coastal validation roadmap and recommends service-life-equivalent carbon assessment. The principal conclusion is that reproducibility, durability and transparent climate accounting—not impressive isolated strength gains—must determine whether variable palm-derived residues can become certifiable engineering constituents.

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Introduction

Concrete decarbonisation is frequently framed as a straightforward matter of substituting part of Portland cement with a lower-emission powder. That framing is incomplete because structural materials are purchased, specified and approved as repeatable products rather than as successful laboratory mixtures. Palm oil fuel ash (POFA), a combustion residue generated at palm-processing facilities, illustrates this mismatch particularly well: high silica content and favourable laboratory performance do not guarantee a uniform supply of reactive powder. A more useful question is how a variable industrial residue can acquire a controlled identity, a documented production history and a verified range of service performance.

The distinction is consequential for Indonesia and other palm-producing economies. Mills may differ in feedstock mixtures, energy recovery practices, boiler operation and ash handling, while concrete plants require predictable slump, setting, strength development and durability. Thus, the industrial value of POFA cannot be inferred from a nominal replacement percentage or a single 28-day compression test. Qualification must connect upstream decisions at the mill with observable characteristics of the ash and with the exposure-specific behaviour of concrete. This review treats the connection as a production and engineering system rather than a collection of isolated experimental results.

An additional material stream makes the challenge scientifically richer. Palm-kernel shells, empty fruit bunches, mesocarp fibres and other palm-derived residues can be converted to biochar by oxygen-limited thermal processing. Unlike mineral ash, biochar is a carbon-rich, often porous solid whose surface chemistry, particle size and water uptake influence cement paste through mechanisms that are not primarily pozzolanic. Whether it improves strength or transport resistance depends on its treatment and dosage; whether it stores atmospheric carbon depends on counterfactual feedstock fate and long-term carbon stability. Combining POFA and biochar without separating these functions risks confusing mineral reactivity with physical water management.

The literature is now substantial enough that another general review of cement replacement alone would offer limited novelty. The recent POFA synthesis examines grinding, heat treatment and

concrete performance, while multiple biochar reviews already survey mechanical properties and sustainability. What remains comparatively underdeveloped is a single translational argument joining variable plant residues, process controls, hydration and pore-scale response, field durability, statistical quality assurance and standard-setting. This article therefore constructs a processing–microstructure–durability–qualification framework and asks which evidentiary claims can be supported today and which must remain explicit research hypotheses.

An increasingly important part of the evidence base concerns investigations conducted after the earlier general reviews. Field-derived chloride profiles, cyclic chloride exposure and recent POFA microstructural studies now permit a sharper distinction between short-term screening success and exposure-dependent performance. The key novelty of this review therefore lies not in claiming an unrecognised material application, but in bringing these heterogeneous findings into a transparent production-to-qualification framework.

The target application is not restricted to one concrete grade or national specification. The review examines structural and non-structural concrete, mortar and related binders, but places special emphasis on reinforced members in humid tropical and chloride-exposed coastal environments. Such conditions make chloride ingress, wetting cycles, carbonation, cover quality and crack control inseparable from material acceptance. The contribution is consequently a decision architecture: which materials deserve further investigation, how promising formulations can be screened, what evidence is needed before field trials, and when a formulation could plausibly enter a certifiable construction supply chain.

Literature Review and Analytical Foundations

Mineral Residues, Reactive Silica and The Hierarchy of Evidence

POFA should be understood as a family of ash products, not as a single chemical substance. Silica-rich particles may act as fillers, provide nucleation surfaces or participate in pozzolanic reactions when amorphous and sufficiently accessible to alkaline pore solution. These contributions occur on different timescales and should not be collapsed into a general claim that every fine ash is reactive. The distinction matters because fineness can raise early strength by improved packing even if chemically available silica is modest. A convincing characterization programme therefore measures composition, phase assemblage, morphology, size distribution and reaction rather than substituting one proxy for another.

Recent concrete experiments illustrate why processing descriptors must be reported together with strength. Torres-Ortega et al. (2026) evaluated several POFA replacement levels at a constant water-to-binder ratio and characterised hydration products and the interfacial transition zone through microscopy and elemental analysis. Such comparisons add useful microstructural evidence, but their scope remains bounded by one ash preparation route, mixture family and curing history; reproducing the relationship across distinct mill sources is the next engineering test. Separately, work on POFA as a modified ultra-high-performance concrete filler reinforces the need to distinguish physical packing from chemically demonstrated reaction.

Loss on ignition, residual carbon and soluble salts provide another layer of complexity. Carbon-rich particles can adsorb admixtures and influence water demand; angular or porous ash can similarly change rheology at unchanged water-to-binder ratio. Conversely, a well-classified, ground ash may behave differently from coarse, as-collected boiler ash. The interpretation of a reported strength increase must accordingly account for superplasticizer dosage, effective water content, reference mixture design and curing regime. Without these controls, a result attributed to pozzolanic activity may partly reflect changes in dispersion, paste volume or packing density.

Strength activity indices are convenient indicators but they do not uniquely quantify the chemistry of a supplementary cementitious material. Accelerated reactivity methods measuring heat release, bound water or portlandite consumption can separate promising materials from largely inert ones, yet they also show biases related to chemistry and reaction speed. Qualification is thus best conceived as a hierarchy: rapid tests for screening, longer-term paste and mortar tests for mechanism, and concrete trials for the proposed service environment. A single short-duration threshold is not scientifically sufficient to infer chloride resistance, shrinkage or steel corrosion behaviour.

Biochar as a Porous Carbonaceous Concrete Constituent

Biochar does not possess one invariant set of engineering properties. Feedstock lignin, cellulose and inorganic fractions interact with pyrolysis temperature, heating rate, atmosphere and residence time to determine carbon yield, volatile content, pore distribution and alkalinity. Low-temperature chars may retain more oxygen-containing groups and volatiles, whereas hotter treatment can alter aromaticity and surface area. These transformations affect affinity for water and admixtures, and they may shift the balance between internal curing and loss of fresh workability. A useful materials taxonomy must therefore report the preparation route as a critical identifier, not merely the biomass species.

In cement matrices biochar can function as a fine filler, a relatively weak or stiff inclusion, a local reservoir of absorbed water, a carbon carrier or, for silica-containing chars, a limited reactive component. Such functions need not occur together. A large biochar aggregate may lower density and conductivity but alter the load-transfer path; fine char may improve particle packing but increase water demand; saturated char may help maintain internal moisture while changing free mixing water. Material qualification should classify char by intended role and replacement basis, because a percentage of cement mass is not interchangeable with the same percentage of aggregate volume.

Composite-specific studies further warn against treating all carbonaceous admixtures as interchangeable. In engineered cementitious composites, biochar incorporation has been associated with altered internal curing and a complex strength–ductility–stiffness response; the resulting optimum cannot be transferred directly to ordinary POFA concrete without testing the fibre system, pore network and replacement basis. Meta-analytic evidence likewise indicates substantial dispersion among reported biochar strength responses, reinforcing the need to identify feedstock and dosage moderators rather than select a single favourable effect.

The carbon-removal argument also requires disciplined accounting. Retaining biogenic carbon in concrete is not identical to permanent negative emissions, particularly where biochar might oxidise, be released at end of life, or be produced from biomass that would otherwise have been used for energy. To claim net removal, the analysis must quantify carbon origin, conversion yield, stable carbon fraction, energy and transport emissions, system boundary,

displacement effects and appropriate permanence assumptions. Carbon storage can complement clinker reduction, but the same climate credit cannot be counted simultaneously by a producer, concrete plant and end user.

Microstructural Causal Pathways

The relevant causal chain is more complicated than particle size leading directly to compressive strength. Treatment changes particle surfaces and mineralogy; these characteristics affect early dissolution, nucleation, hydration kinetics, packing and interfacial bonding; the resulting solid phases and pore network then govern transport and cracking. Measurements should therefore connect several levels of observation. X-ray fluorescence and diffraction describe chemistry and phases, microscopy describes spatial arrangement, calorimetry provides hydration timing, and transport measurements evaluate whether proposed densification remains functionally important under realistic saturation states. Figure 1 summarises the intervening variables and the feedback from engineering qualification to production controls.

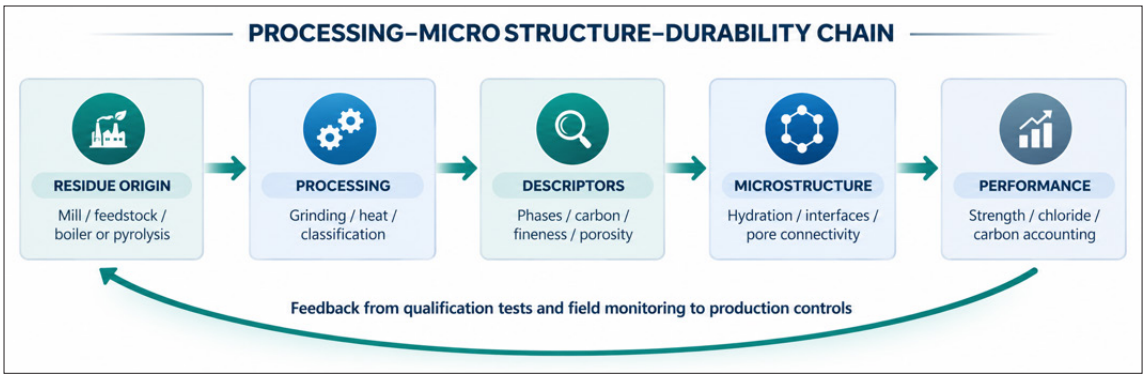


Figure 1: Material Production Conditions Propagate Through Microstructure to Verified Concrete Performance (Conceptual Synthesis).

The diagram emphasizes why source and process descriptors are necessary inputs to a durability claim. Feedback is not decorative: a failed corrosion or transport assessment should cause the source, treatment or dosage envelope to be revised, followed by retesting under the same exposure assumptions. The direction of feedback makes this a closed-loop qualification system rather than a one-way account of materials development.

A dense matrix may lower ionic transport without eliminating all deterioration mechanisms. Diffusivity depends on connectivity and tortuosity, electrical response also depends on pore-solution chemistry, and cracking creates preferential routes that cannot be inferred from intact laboratory paste alone. Furthermore, a change that reduces capillary suction under one preconditioning protocol may not produce an identical effect under prolonged seawater saturation. Claims about durability should therefore specify the exposure, transport mechanism and measurement method. This mechanistic perspective is particularly important when fine mineral particles and porous carbon are introduced in the same mixture.

Method: Critical Qualitative Literature Review

The study adopts a critical qualitative literature review, not a systematic literature review or statistical meta-analysis. Its purpose is to explain mechanisms, reconcile conflicting observations and formulate a proposed route to engineering qualification rather than estimate a single pooled effect size. Literature was sought across journal publications from 2020 to 2026, emphasizing articles on POFA pretreatment, cement reactivity, biochar incorporation, hardened performance, durability, carbon accounting and material assessment. Established standards are discussed as engineering comparators, but the journal evidence base is kept separate from normative specification texts.

Search concepts combined palm oil fuel ash, supplementary cementitious material, grinding, amorphous silica, loss on ignition, biochar, kernel shell, empty fruit bunch, internal curing, concrete, pore structure, chloride, sulphate, carbonation, microstructure and life cycle assessment. Searches used publisher and scholarly indexing pages and were supplemented by backward citation tracing from major reviews. Screening was purposive: primary studies were preferred for specific mechanistic claims, while recent review articles supplied broader context and identified disagreements. A publication was not assigned greater evidentiary weight merely because its reported strength gain was large.

The synthesis used a qualitative coding matrix with five dimensions: input variability, processing intervention, measured material descriptor, concrete response and potential qualification implication. Each study was interpreted alongside its binder system, replacement basis, curing history, comparator and exposure protocol. Conflicting outcomes were retained as informative evidence of conditional behaviour rather than treated as noise to be discarded. Because the method is interpretive and purposefully selective, it does not claim exhaustive retrieval, PRISMA compliance, formal risk-of-bias scores or numerical certainty about average effects.

A further distinction was made among three evidence categories. Direct evidence describes outcomes measured on a named POFA or biochar specimen; transferable evidence derives from other agricultural ashes, biochars or SCM test-method investigations; and proposals are engineering procedures not yet validated as POFA-specific consensus criteria. This classification is important when applying biochar results derived from wood, rice husk or sludge to palm biomass. Those studies can suggest mechanisms and test designs, but they cannot establish the properties of palm-kernel-shell or empty-fruit-bunch chars without independent confirmation.

Results: Thematic Findings

From Milling and Thermal History to Material Quality

The first recurring finding is that the processing history cannot be reconstructed from the label POFA. A mill may burn shell, fibre

and other residues in changing combinations, while combustion completeness, air supply, furnace temperature and collection position influence the proportion of unburned carbon and the ash particle population. Downstream stockpiling can introduce moisture or contamination. These variations provide a plausible explanation for divergent published observations about water demand and strength. They also imply a practical control point: sampling and segregation at collection may matter as much as grinding after the material reaches a concrete plant.

One implication of the mineral-ash evidence is that laboratory treatment must be described as a reproducible manufacturing window, not simply a grinding duration. A reproducible window should report specific energy per tonne, residence time, feed size and classification yield alongside the accepted particle-size distribution and loss-on-ignition envelope. These measures will allow a producer to determine whether an improvement in transport resistance can be achieved consistently rather than only with energy-intensive laboratory batches.

Mechanical processing is commonly beneficial but not costless. Grinding can reduce coarse particles and increase surface area, thereby supporting closer packing and potentially exposing reactive phases. Nevertheless, ultrafine classification may demand additional electricity, capital expenditure and dust controls. It may also increase agglomeration or admixture demand if the resulting particles are very fine. The relevant engineering objective is therefore not maximum fineness in isolation but the least resource-intensive preparation yielding reliable reactivity, acceptable rheology and target durability. A plant-scale specification should define a practical particle-size envelope and report the energy required to produce it.

Thermal reprocessing can remove residual carbon and alter mineral phases, but its effect depends on time, temperature and original ash chemistry. Over-processing might diminish some reactive amorphous fraction or erase the environmental benefit through additional fuel demand. Chemical washing or activation can address selected contaminants, although the disposal of wash liquor and effects on subsequent mixture chemistry require attention. Comparisons among untreated, ground, calcined and chemically treated ash should therefore be conducted using the same parent batch wherever possible. That paired design can identify which intervention causes an observed performance difference rather than confounding treatment with feedstock.

Particle characterization is most informative when it reflects population heterogeneity. Reporting only mean diameter or Blaine fineness conceals coarse tails, multimodal distribution and shape effects. Characterization of ash used for engineering qualification should include representative sampling frequency, XRF major oxides, XRD phases, thermogravimetric carbon estimate where appropriate, particle-size distribution, density, moisture, soluble ions and admixture compatibility. Scanning electron microscopy can explain morphology, but visual micrographs are not substitutes for quantitative batch control. A material passport linking test results to boiler operating records could make scattered laboratory findings transferable to production.

The emerging evidence on mineral blends indicates that POFA need not perform alone. Combinations with limestone powder, fly ash or other constituents can adjust particle packing, provide additional reactive chemistry or recover workability. However, attributing benefits to POFA becomes difficult unless mixture design separately controls each contributor. Ternary systems should be investigated through factorial mixtures with clear replacement bases and water adjustments. This would make it possible to distinguish synergistic hydration from the simpler effects of diluting cement, increasing paste volume or changing granulometry. Such discrimination is especially important when claims are made about high-volume replacement.

Palm-Residue Biochar: Production and Formulation Contrasts

For palm-derived biochar, pyrolysis is a controllable manufacturing step rather than incidental combustion. Palm kernel shell typically behaves as a relatively dense lignocellulosic feedstock, whereas empty fruit bunches and mesocarp fibres may differ in moisture and mineral content. Their chars should not be treated as interchangeable, especially where water absorption, soluble potassium or residual ash are relevant to hydration. Published non-palm biochar experiments consistently show that preparation temperature and particle size can change the strength response. The translational research need is to test representative palm feedstocks under directly comparable thermal histories and concrete formulations.

Use-specific qualification is particularly important for foamed and other non-structural concrete products. Recent POFA foamed-concrete research offers a plausible initial market segment because these applications can establish functional and environmental requirements without implying that the same material is ready for critical reinforced members. The transition from product category to broader structural certification still requires new evidence on exposure, variability and quality control.

A proposed classification separates chars intended for microfilling, water-mediated internal curing, lightweight aggregate and carbon-retaining filler applications. Each class demands a different acceptance test. Microfillers call for particle size, dispersibility and admixture compatibility; internal-curing chars require absorption–desorption curves and effective water accounting; lightweight aggregates require density, crushing resistance and volumetric stability; carbon-retaining fillers require carbon content and persistence assessment. A single universal substitution percentage obscures these distinctions. The binder and aggregate pathways should remain distinct in reporting, even when they are compared within the same programme.

High porosity can have beneficial and harmful consequences simultaneously. Water stored in connected biochar pores can be released during hydration and reduce self-desiccation, but the same surface may withdraw mixing water before placement or create defects if poorly wetted. Pre-saturation helps only when its moisture state is measured and total batch water is reconciled. Likewise, fine particles may provide nucleation sites but excessive dosage can impair workability or introduce a weak interface. Consequently, moisture conditioning, addition sequence, mixing energy and admixture adsorption must be part of the method report rather than left as laboratory routine.

Evidence derived from sludge, rice husk, wood and other non-palm feedstocks is valuable for understanding mechanisms yet has bounded external validity. A char reported to enhance early hydration at one pyrolysis temperature does not establish that palm kernel shell char will exhibit the same kinetics. Inorganic ash content, soluble salts and pore architecture vary across feedstocks, while concrete preparation can mask these differences. Palm-focused research should therefore include feedstock-controlled

crossover experiments and report both mass- and volume-based dosage, because carbonaceous particles often have markedly different densities from mineral powders.

Direct comparisons between POFA and biochar suggest a conceptual opportunity for hybrid composites. POFA supplies a possible source of reactive siliceous material, whereas biochar can support physical moisture management and carbon retention. Yet their simultaneous addition could intensify water demand, change admixture sorption or create competing effects on carbonation. A hybrid mix cannot be assumed superior to either constituent individually. Evidence of synergy would require the interaction term in a factorial design to be significant and mechanistically interpretable, not merely the hybrid sample outperforming a plain-cement control.

Fresh Properties, Hydration and Pore Evolution

Across the literature, fresh performance is sensitive to both the chemistry and surface geometry of additions. Untreated coarse POFA can increase the water or superplasticizer required for comparable flow, while optimized fines sometimes improve packing and rheological response. Biochar may absorb water and alter yield stress, especially where particles are dry, very porous or poorly dispersed. These effects should be tested under constant effective water-to-binder ratio and controlled admixture concentration. Otherwise, a measured compressive-strength difference may reflect inconsistent hydration water rather than the intended mineral or carbon modification.

Hydration calorimetry is a useful bridge from particle properties to concrete performance because it registers changes in induction, acceleration and cumulative reaction heat. Ground POFA may provide fine surfaces for early nucleation while later pozzolanic reaction consumes portlandite, but the distinction requires supplementary evidence from phase analysis or bound-water measurements. Biochar can affect the local hydration environment through water release and available surface area, not necessarily through consumption of calcium hydroxide. Establishing these mechanisms requires matched paste experiments followed by mortar and concrete verification, because aggregate volume and curing can obscure effects seen in paste.

Microstructure should be assessed as a time-dependent, spatially heterogeneous phenomenon. Electron microscopy may reveal denser hydration products around optimized ash particles; thermogravimetry can indicate changes in calcium hydroxide; porosimetry and tomography can reveal pore networks at different scales. No single method perfectly measures transport-relevant connectivity, and conventional mercury intrusion results require cautious interpretation. A robust mechanistic claim should triangulate at least two independent observations and correlate them with a transport property. This is particularly important for biochar, where pores within the additive and pores connected through the cement matrix have very different implications.

Recent evidence from POFA mixtures at multiple replacement levels has applied scanning electron microscopy and energy-dispersive spectroscopy to the matrix and interfacial transition zone. That evidence is relevant because it makes claims about hydration-product continuity more testable, although microscopy remains primarily local and does not by itself establish the connected transport pathway in full-scale concrete. Future campaigns should pair spatial observations with transport and shrinkage data obtained on matching specimens and replicated source batches.

The interfacial transition zone deserves greater attention than it commonly receives in screening studies. Ash particles, biochar particles and coarse aggregates can each establish local differences in packing, hydration and stiffness. Excess biochar may behave as a defect or a compliant inclusion, whereas well-dispersed fine powder may improve local continuity. Mechanical behaviour under flexure and cyclic stress is therefore not determined by mean bulk porosity alone. Nanoindentation, backscattered imaging and fracture analysis can help test whether an apparently improved bulk response also maintains reliable interfacial load transfer under service loading.

Strength, Deformation and Thermal Response

The mechanical literature suggests that carefully processed POFA can sustain competitive strength, particularly when curing allows time for later reaction. Results are nevertheless conditional on fineness, cement chemistry, binder fraction and workability control. A claim of equivalent compressive strength should be reported over multiple ages and batches; a one-age match does not imply equivalent modulus, flexural capacity, creep or shrinkage. Design acceptance should also consider scatter and lower-tail performance rather than only the average of a few cubes. These statistical issues are central when materials are made from heterogeneous agricultural residues.

A recent quantitative synthesis of Portland-cement systems confirms that reported changes in biochar-modified compressive strength are heterogeneous rather than universally favourable. This evidence supports examining the moderators of mix design and carbon particle treatment instead of translating pooled benefits into an approval threshold. High-strength engineered cementitious composite trials add a distinct performance class, but their fibre bridging and tensile requirements must not be confused with those of conventional reinforced concrete.

Biochar additions show a particularly strong dosage dependence. Low quantities of suitably prepared fine char sometimes improve measured mechanical response, while larger quantities or unsuitable particle morphologies can lower strength or alter stiffness. Observations should be interpreted according to replacement function: binder displacement reduces reactive binder mass, whereas fine-aggregate replacement changes packing and paste demand. Lightweight and thermal benefits may justify different limits from structural-strength applications. It would be scientifically misleading to present an optimum reported for wood- or sludge-derived char as a verified universal optimum for palm biomass.

Volumetric stability is also critical in tropical construction. High temperature during placement, varying curing access and early drying can create cracking even when nominal permeability is low. Fine POFA can affect pore refinement and binder reaction, whereas preconditioned biochar may serve as an internal moisture source that mitigates shrinkage in selected systems. Yet some contaminants and alkalis have been associated with unfavourable shrinkage outcomes in biochar mixtures. An appropriate qualification programme should measure autogenous and drying shrinkage, restrained cracking propensity and creep where relevant, with replicate specimens conditioned for the actual exposure.

Thermal and fire performance require separate interpretation. Biochar may reduce heat conductivity by introducing low-density pores, but increased porosity does not automatically improve resistance to cracking or residual strength after severe heating. Similarly, POFA-rich concrete exposed to elevated temperatures

can exhibit phase changes and damage patterns that differ from those observed at ambient conditions. Claims about fire resistance must include the temperature-time history, residual strength and damage mechanism, and ideally spalling response for dense structural formulations. Energy-saving insulation benefits cannot be substituted for structural fire qualification.

Transport, Chloride Exposure and Reinforcement Corrosion

Chloride transport is among the most decision-relevant durability criteria for coastal infrastructure. POFA may refine capillary structure and reduce effective chloride mobility when properly processed and cured, but results depend on saturation, binding chemistry, crack condition and test duration. Rapid electrical indicators can be confounded by pore-solution conductivity and should not be reported as direct diffusion coefficients. For reinforced concrete, the crucial question is how the new binder influences time to corrosion initiation at a specified cover depth and environment. That requires linking laboratory transport metrics to a service-life model with explicit uncertainty.

The most decision-relevant new POFA evidence combines controlled transport experiments with longer-duration marine observations. Senawang et al. (2026) assessed strength, water permeability and chloride resistance of concrete containing several levels of ground POFA up to 90 days; their performance rankings varied across indicators, indicating that high strength and low water permeability do not necessarily identify the same mixture. Chalee et al. (2023) used chloride profiles from specimens exposed to marine conditions for up to ten years to construct a predictive model. The latter model is restricted by its calibrated water-to-binder ratios, exposure conditions and unidirectional ingress assumptions, so it cannot be adopted as a universal service-life equation without local validation.

Evidence from marine exposure demonstrates the value of examining concrete as a system rather than treating low permeability as an isolated material attribute. Extended curing, surface wetting, tidal cycles and exposure duration all influence ingress, while aggregates, cover thickness and workmanship shape the effective field protection. A laboratory mix giving favorable chloride results may still be unsuitable if high admixture demand disrupts batching reproducibility. The relevant acceptance proposition is thus exposure-class specific: an admissible composition and its demonstrated performance under a documented curing and placement procedure, not approval of POFA in abstract terms.

Biochar can change chloride or sulphate resistance through several competing pathways. Finer particles may reduce connected macropores or maintain hydration through internal curing; poorly dispersed particles may create connected defects; soluble species can modify transport and chemical equilibria. Comparative studies of silica-rich and comparatively inert biochars highlight why surface chemistry and ash fraction matter. Evidence from those studies offers hypotheses for palm biochar, not direct validation. Hybrid POFA–biochar trials should include the control, each component alone and their combination to isolate interaction effects under identical exposure and curing histories

A complementary investigation of metakaolin–POFA blends under repeated chloride wetting and drying has reported improved later-age performance for some mixtures but also highlighted time-dependent deterioration during prolonged cyclic exposure. This finding argues against treating any single rapid electrical test as a sufficient proxy for long-term penetration or corrosion risk. In particular, favourable short-term charge-passed classifications should be corroborated by actual chloride profiles, binder chemistry, crack measurements and natural-exposure observations where the consequence of failure is high

Reinforcement corrosion is the endpoint that often remains missing from academic screening. Chloride migration, bulk resistivity and water absorption do not independently determine corrosion rate once depassivation occurs. The transition depends on oxygen supply, moisture, cracks, steel–concrete interface and electrochemical conditions. Field-relevant trials should monitor corrosion potentials, polarization-based corrosion indicators where appropriate, chloride profiles and cracking over sufficiently extended periods. Causation should not be inferred from a single electrical transport measurement. This reinforces the need to qualify concrete mixtures for specified infrastructure uses rather than simply approving an ash powder.

Other Deterioration Pathways and Combined Exposures

Sulphate attack and acidic conditions illustrate why one-dimensional durability claims are unreliable. Sulphate performance depends on binder aluminates, permeability, pH, external solution composition and physical damage, while acid resistance can involve direct dissolution of cement hydrates. Studies of POFA-containing alkali-activated systems are informative but cannot automatically be transferred to ordinary Portland cement binders. A defensible assessment must classify chemistry and binder family, report solution renewal and exposure duration, and distinguish mass loss, expansion and strength retention. These observations should be interpreted against the deterioration mechanism being simulated rather than as interchangeable performance indices

Chemical-safety studies provide a further transferable, but non-palm-specific, line of evidence. Experiments on cement hydrates have shown that the mobility of potentially hazardous ions reflects binding and leaching mechanisms, while modified biochar systems can change the immobilisation of selected metals. Neither result guarantees safe use of an individual palm-ash batch, because precursor contamination, pH evolution and leachate conditions remain material-specific. Proposed qualification should consequently use representative POFA and palm-biochar batches, assess changes after carbonation and crushing, and interpret releases against the applicable environmental limits.

Carbonation creates a particularly important qualification paradox. It can immobilize carbon as carbonate under controlled curing and may locally densify pore structures, yet progressive carbonation can reduce alkalinity around reinforcing steel. Biochar-assisted carbonation therefore should not be labeled a durability gain without specifying whether the application is unreinforced masonry, precast components or reinforced structural concrete. The carbonation front, CO_2 concentration, moisture history and alkali reserve require explicit measurement. A material can support accelerated carbon mineralization and still need restrictions in service environments where steel passivation is essential.

Freeze–thaw results in the broader biochar literature are not a primary design driver for much of coastal Indonesia, but they demonstrate the necessity of exposure-specific qualification. Conversely, warm humid conditions and intermittent intense drying can change internal saturation and crack development even without freezing. Tropical qualification should prioritize sustained chloride exposure, carbonation under realistic relative humidity, thermal cycling, wet–dry repetitions and combined mechanical loading. Full factorial exposure testing is expensive, so early screening should rank the most plausible coupled mechanisms for

a particular structure before selecting long-term demonstrations.

Leaching and environmental safety must not be omitted simply because the feedstock is agricultural. Ash and biochar can carry soluble salts, metals or organic residues depending on combustion conditions and material handling. A cement matrix may immobilize some constituents initially, but carbonation, cracking, abrasion and end-of-life crushing can change release behaviour. Screening should combine chemical inventory and appropriate monolithic or granular leaching tests, choosing exposure conditions relevant to product use and eventual demolition. Environmental qualification is a distinct requirement from mechanical adequacy; passing a compressive-strength test cannot establish safe release behaviour.

Lifecycle and Economic Interpretation

For service-life comparisons, the functional unit should be selected before emissions are calculated. A nominal cubic metre of concrete may not be equivalent when two formulations require different cover depth, repair frequency or design service life; conversely, a tonne-of-binder comparison hides the structural function supplied by the mixture. A defensible assessment should publish both product-stage embodied emissions and a clearly scenario-defined functional comparison, including uncertainty in field durability, retained carbon and end-of-life processing.

The embodied-carbon benefit of POFA is conditional on displacement and process burdens. A credible inventory credits only cement genuinely displaced at the same functional performance, then counts ash collection, drying, milling, possible recalcination, admixtures, transport, mixing and waste management. If additional binder is required to recover strength, the nominal POFA replacement percentage may overstate avoided clinker emissions. Comparisons should therefore use a functionally equivalent concrete volume and, when lifetime differs, a common service-life performance basis. Published low-carbon narratives that stop at material substitution miss important trade-offs.

Biochar carbon accounting adds further questions about feedstock counterfactuals and persistence. Residues burned for useful mill energy cannot necessarily be reassigned to a pyrolysis facility without considering replacement energy. Biochar processing may produce coproduct heat, gas or liquids, but allocation among these streams changes footprint calculations. Moreover, retained biogenic carbon is only a defensible removal claim with explicit assumptions about long-term storage and end-of-life fate. Sensitivity analysis should vary electricity mix, transport distance, stable carbon fraction, pyrolysis yield and alternative residue management. A negative result under one set of assumptions is not a universal material attribute.

Economic feasibility depends on material consistency as well as unit processing price. Fine grinding may be expensive, but rejection rates, workability variability, laboratory testing and potential failures can dominate the downstream cost of an unreliable SCM. Conversely, a predictable grade with traceable data may justify quality-control expenditure by reducing plant trials and specification uncertainty. Regional hubs for sorting, testing and classifying palm residues could distribute fixed analytical costs across several mills. The viable business model is likely to resemble certified mineral additions with monitored process envelopes rather than informal sale of untreated ash.

The strategic value of a hybrid approach must be tested against simpler alternatives. A conventional optimized binder using widely available SCMs, improved clinker efficiency, reduced overdesign or better curing may deliver lower risk at comparable carbon savings. Palm-derived additions are attractive when located near mills and construction demand, with reliable collection and clean processing energy. The correct decision is not to maximize waste utilization regardless of outcome but to select the option with the best verified balance of embodied emissions, durability, cost and supply resilience. A comparative decision matrix is therefore preferable to a single circular-economy narrative.

Discussion and Analysis

Explaining Inconsistent Results and Testing the Hybrid Hypothesis

The most important interpretive finding is that variation in input material and protocol plausibly explains a large share of divergent performance results. Studies vary in original feedstock, burning and pyrolysis conditions, processing intensity, water correction, admixture dosage, reference binder, curing and replacement basis. Aggregating reported strength percentages without these descriptors would conceal causal heterogeneity. An engineering-grade literature synthesis should instead ask which processing pathways produce reproducible material descriptors, and which descriptors predict desirable concrete properties across multiple independent batches. This shifts research incentives from spectacular single-mixture results to robust causal explanations.

The hybrid hypothesis is attractive but remains insufficiently validated for palm-specific materials. It posits that a reactive, well-ground mineral fraction can support hydrate formation and pore refinement, while a carefully conditioned carbon fraction manages internal moisture and retains stable carbon. The counter-hypothesis is equally plausible: admixture adsorption and high water demand could negate potential benefits, or carbon-related porosity could compromise transport resistance. Factorial experiments should compare at least four cells—neither addition, POFA only, biochar only and both—at matched paste volume and effective water. Interaction estimates would then indicate whether a true synergistic effect exists.

The analysis also shows why a single universal optimal dosage is unlikely. The mass-based replacement fraction captures very different changes in cement chemistry and material volume for dense silica ash and low-density carbon. Even within one material category, surface area and water absorption can vary substantially. Optimization should be multi-objective, seeking robust workability, strength, durability and carbon outcomes rather than the maximum of one laboratory response. A feasible optimum may be a conservative interval supported by several production batches, not a nominal point estimate reported from one local experiment.

A Proposed Performance-Based Qualification Framework

Figure 2 converts the evidence into a stage-gated qualification proposal. Gate A establishes traceable source identity and preliminary safety; Gate B validates the processing envelope and batch-to-batch material descriptors; Gate C demonstrates binder compatibility and reactivity where the intended role requires it; Gate D verifies structural and durability performance for the target exposure; and Gate E validates pilot production, life-cycle claims and field monitoring. Failure at an early gate triggers reformulation or reclassification rather than an automatic ban. The approach is consistent with the rationale for rapid SCM screening while preserving the need for concrete-scale evidence.

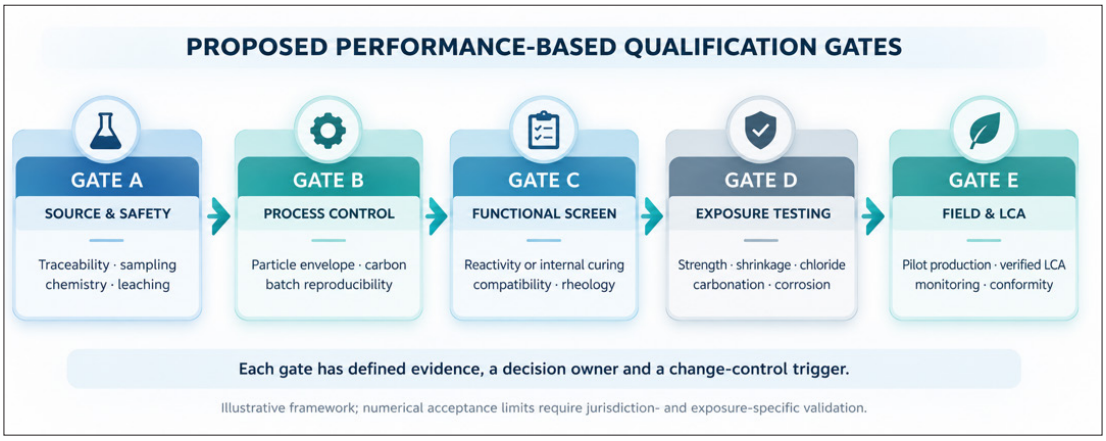


Figure 2: Proposed Role-Specific Qualification Gates, From Provenance to Independent Pilot Verification; Not an Approved Normative Standard.

A minimum POFA passport should include mill and boiler identity, feedstock mix where available, collection location, date, pretreatment history, moisture, loss on ignition, oxide composition, phase fraction, density, particle-size distribution, soluble chlorides and sulphates, and a reactivity indicator. Biochar passports should add pyrolysis atmosphere, temperature and residence time, fixed and volatile carbon, ash fraction, elemental composition, particle porosity, absorption/desorption and leaching information. These fields are proposed reporting requirements, not yet a harmonized code. They should be accompanied by sampling plans and independent interlaboratory studies establishing measurement precision.

At Gate C, screening tests should be tied to the constituent's declared engineering role. For POFA as a reactive SCM, a rapid reactivity measure, calorimetry, strength development and compatibility tests are relevant. Biochar intended principally as internal-curing filler should be assessed for moisture kinetics, rheology, effective water and long-term mechanical effects rather than being rejected because it lacks strong pozzolanic activity. Hybrid mixes require both role-specific checks. The gate should distinguish qualification of the constituent from qualification of the finished concrete formulation, because even a compliant powder may perform poorly in an unsuitable binder system.

Gate D should be structured around explicit use categories: non-reinforced products, ordinary reinforced inland structures, marine reinforced elements and specialty lightweight or thermal applications. For each category, the owner and engineer would select relevant strength, modulus, shrinkage, transport, carbonation, corrosion, heat and leaching measurements. Where ASTM, EN or ISO test methods are invoked, the applicable editions, conditioning procedures and local acceptance thresholds must be confirmed by the adopting authority. This review does not propose invented universal cutoffs, because durability limits must be calibrated to exposure class, design life and jurisdiction.

The qualification matrix in Table 1 specifies the evidence package proposed for each gate, rather than assigning universal numerical pass–fail criteria. The decision authority should be identified in a project-specific quality plan, and the qualified operating envelope should be documented so that source changes, equipment changes and anomalous results trigger explicit reassessment. Importantly, passing an early gate confirms suitability for further evaluation; it never substitutes for the concrete-scale exposure testing required at a later gate (Al-Shmaisani et al., 2022; Senawang et al., 2026).

Table 1: Proposed Evidence Packages and Change-Control Triggers for The Five Qualification Gates (Author Synthesis; Not A Normative Specification).

Gate / decision	Demonstration required	Minimum evidence (proposed)	Requalification trigger / disposition
A · Source/safety	Mill and batch identity; residues and chemical hazards	Provenance records, representative sampling, oxides, LOI, soluble ions and leaching tests	Release to controlled processing only; source mix or contamination changes require re-screening
B · Process control	Reproducibility of ash/char production	Grinding/pyrolysis envelope, size distribution, carbon, moisture, batch statistics	Recalibrate following equipment, fuel, temperature or particle-envelope changes
C · Functional screen	Suitability for declared material role	SCM reactivity and strength development, or biochar absorption–desorption, rheology and compatibility	Reject or redesign mix when chemical/ physical function is not reproducible
D · Exposure testing	Concrete suitable for its target exposure class	Strength, cracking/shrinkage, chloride/ carbonation transport, corrosion where reinforced; relevant leaching	Approval applies only to the verified concrete and exposure/curing envelope
E · Field and LCA	Independent product and environmental claims	Pilot batches, natural exposure, conformity tests, service-life LCA, traceable surveillance	Suspend or change approval after systematic deviations or unverified carbon claims

The matrix deliberately treats provenance, material function, exposure performance and environmental evidence as different acceptance decisions. A supplier may pass a material-screening test but fail a concrete-mixture durability test; likewise, a technically adequate product may need its environmental claim withdrawn if life-cycle assumptions cannot be independently substantiated. This separation provides an auditable basis for qualification without inventing universal acceptance thresholds.

Statistical quality assurance is essential to the transition from a paper to a product. Pilot plants should record distributions rather than isolated averages, use control charts on key indicators and define actions when a batch falls outside the qualified processing envelope. Independent replicate batches, retained samples and periodic round-robin testing would help distinguish material variability from test uncertainty. Change control should be triggered by new feedstock proportions, boiler retrofit, altered grinding equipment or a different pyrolysis regime. A batch passport could then connect material production with the concrete plant's mix approval and asset owner's inspection record (Hamada et al., 2020b; Hamada et al., 2022).

Tropical/Coastal Engineering Roadmap for Indonesia

For practical implementation, the five gates should be operated as a traceable record: source sampling forms and certificates at Gate A, process control charts at Gate B, role-specific material test reports at Gate C, approved exposure-class concrete dossiers at Gate D, and lifecycle declarations plus surveillance reports at Gate E. This staged record would provide a documented basis for procurement and third-party review while still permitting different constituent roles and locally calibrated performance limits. This audit trail also gives infrastructure owners a means of detecting whether an approved mix has departed from its qualified production window.

Indonesia offers a compelling regional setting because it combines palm-processing residues, major concrete demand and many humid or maritime exposure regimes. Yet a national pathway should not presume uniform logistics: mill proximity, access to low-carbon grinding power, laboratory capacity, chloride exposure and concrete-plant scale vary substantially. Initial trials should be geographically clustered around traceable mills and accredited testing facilities. Pilot sites can include non-critical precast products before escalating to reinforced coastal members. This sequencing reduces public risk while generating locally credible evidence of material repeatability, environmental safety and long-term performance.

Figure 3 sets out the recommended research-to-standards roadmap. The first phase maps residue sources and creates reference material batches; the second builds interlaboratory test precision and processing–property databases; the third validates product classes and prototype concrete under accelerated and natural exposures; and the fourth develops specifications, conformity assessment and field-monitoring obligations. These phases are not fixed calendar promises. Progress should depend on demonstrated evidence and the ability of responsible laboratories, producers, engineers and public authorities to repeat the results under realistic operating conditions.

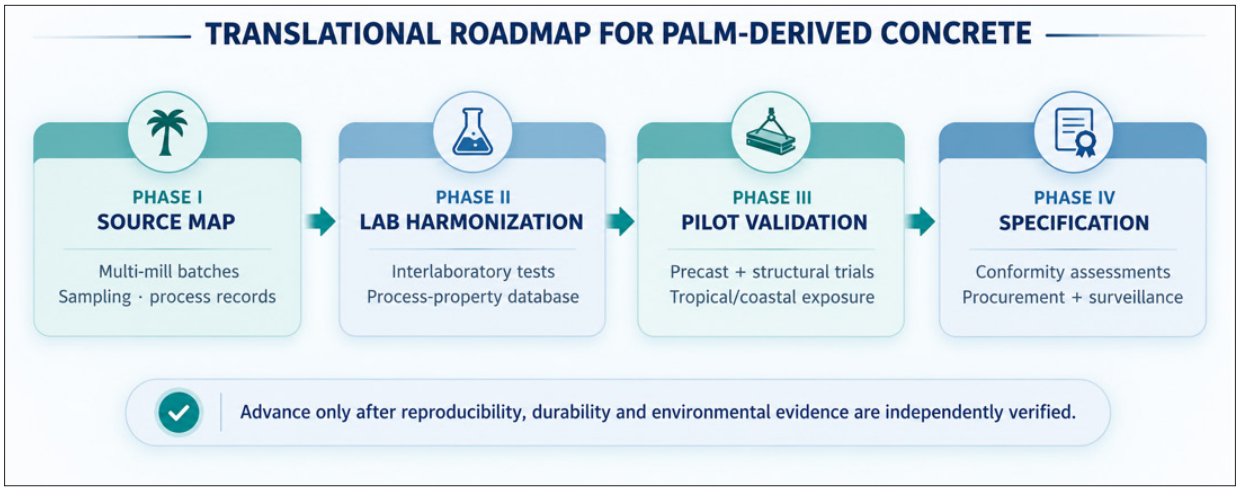


Figure 3: Proposed Evidence-Gated Indonesian Pathway from Source Characterization to Specification and Surveillance

The translational sequence also benefits from explicit failure criteria at pilot scale. For example, interlaboratory disagreement in ash reactivity should lead to method calibration before plant certification, while inconsistent chloride performance across production batches should prompt review of moisture conditioning, fines control and mixing protocols. Recent marine transport and cyclic-exposure research offers a basis for selecting these tests but not for imposing an unvalidated POFA-specific national threshold.

Special care is needed for corrosion-related acceptance. Marine reinforced members should not be approved solely on compression and a rapid electrical indication; evidence should include chloride profiles, diffusion-relevant tests, crack susceptibility, resistivity interpretation, cover specifications and long-term exposure where feasible. Water absorption alone does not resolve reinforcement protection. For applications with limited access for repair, the qualification burden should rise with the consequence of failure. Conversely, unreinforced blocks or internal finishes can follow a different, proportionate pathway after environmental safety and functional performance are established.

The roadmap should also address institutional incentives. Mills may benefit from avoided ash disposal; processors from selling graded material; concrete producers from reliable workability; and infrastructure owners from certified longevity and transparent embodied-carbon declarations. These benefits do not necessarily accrue to the same actor. Procurement should therefore reward verified functional performance and transparent product data,

not only low material cost or circularity language. Independent testing and interoperable batch identifiers can reduce information asymmetry, while public demonstration assets provide the long-term observations that private producers alone may struggle to finance.

Research Priorities and Falsifiable Propositions

Five research priorities follow. First, establish multi-mill reference samples that represent seasonal and operational variability. Second, conduct paired processing trials that isolate grinding, calcination and particle classification without changing the parent ash. Third, produce palm-specific biochar under controlled pyrolysis and moisture-conditioning regimes. Fourth, test hybrid mixtures through interaction-sensitive experimental designs with equivalent effective water and paste volume. Fifth, combine accelerated tests with outdoor tropical and coastal exposure monitoring. Each priority should define an outcome that could disconfirm the preferred hypothesis, not merely collect evidence of potential benefit.

A first falsifiable proposition is that a small set of measurable descriptors—accessible amorphous silica, residual carbon, size distribution, surface area and soluble salts—predicts much of the performance variation in qualified POFA sources. A second is that preconditioned palm biochar can improve hydration or shrinkage only inside a bounded absorption–dosage window. A third is that hybrid benefits, if present, depend on interaction between mineral reaction and moisture regulation and cannot be explained by adding the benefits of separate constituents. These propositions require external validation rather than calibration against the same batch used to formulate them.

A fourth proposition is that service-life-adjusted carbon comparisons will reorder formulations ranked solely by clinker replacement. Processing energy, supplementary admixtures, rejected batches, earlier repair and carbonation-related durability losses may offset some nominal savings. A fifth is that traceable quality assurance substantially reduces the between-batch variation that otherwise obstructs specification. Both propositions lend themselves to collaboration among mills, certified laboratories and infrastructure asset owners. They also bring environmental analysis closer to engineering decision-making, where reliability and life-cycle cost are as important as an impressive single carbon number.

The review has limitations. It is not an exhaustive systematic review; source selection is purposive and the included studies have heterogeneous test methods and limited direct evidence on palm-specific biochar in reinforced coastal structures. No pooled estimate, numeric universal optimum or proposed performance threshold should therefore be interpreted as established consensus. Recent reviews also overlap with some included primary studies, making it important not to treat their conclusions as independent replication. These limitations strengthen rather than weaken the case for common reporting standards, round-robin precision studies and verified field exposure before broad structural acceptance.

Conclusion and Recommendations

POFA and palm-derived biochar offer complementary but fundamentally different possibilities for lower-carbon concrete. POFA can be engineered as a reactive mineral addition when processing produces suitable silica accessibility, fineness and compatible fresh properties; biochar can provide porous physical functions and retained biogenic carbon when production and water state are carefully controlled. Neither material is inherently a certifiable engineering constituent. Their performance depends on feedstock, processing, binder chemistry, mixture design and exposure, while optimistic climate claims must survive full life-cycle and permanence scrutiny.

The proposed pathway begins with traceable material identity, proceeds through role-specific characterization and process control, and culminates in concrete-scale exposure qualification, independent conformity assessment and pilot-field surveillance. Tropical coastal applications demand especially stringent evidence for transport, cracking and reinforcement corrosion, while less consequential unreinforced uses permit appropriately proportionate testing. Hybrid POFA–biochar mixes should be treated as testable hypotheses rather than assumed synergies. Industry, researchers and regulators should prioritize multi-source trials, interlaboratory repeatability and service-life-equivalent carbon assessment so that palm residues can progress from promising waste valorization to reproducible, defensible and ultimately standardizable construction products.

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