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Optimization via Response Surface Methodology of Palm Kernel Shell Biochar for Cementitious Replacement: A Comprehensive Review

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Abstract

The cement industry's high CO_2 footprint (~8% of global emissions) has led to intensive research on supplementary cementitious materials (SCMs) from waste. Palm kernel shell (PKS) biochar — a carbon-rich product of biomass pyrolysis — is emerging as a low-cost carbonaceous filler and multifunctional cementitious additive that can partially replace cement and sequester CO_2. This paper presents a full A–Z review of PKS biochar (PKSB) as a cement additive, with emphasis on optimization via Response Surface Methodology (RSM). Conventional SCMs are reviewed first, alongside the motivation for using biochar from palm waste. PKSB production (pyrolysis parameters, yield, carbon content) and its physicochemical properties (chemical composition, surface area, reactivity) are then summarized, clarifying why PKSB functions primarily as a carbonaceous filler and nucleation agent rather than a true pozzolan. PKSB applications in cementitious materials are subsequently discussed: effects on fresh properties (e.g., reduced slump due to water absorption), mechanical performance (compressive and flexural strength, optimal replacement levels), durability (porosity, permeability), and microstructure (SEM and hydration phases). The core of the review covers RSM fundamentals (designs such as Central Composite and Box–Behnken, statistical analysis including ANOVA, R^2, p values, lack-of-fit and adequate precision) and their application to optimizing PKSB production and mortar mix design. A comprehensive table summarizes all published RSM studies involving PKSB (with variables, design, responses, optimum conditions, key findings). Environmental and economic aspects are analyzed: carbon footprint benefits (LCA studies report up to ~38% emission reduction relative to control), CO_2 sequestration (14.4 kg CO_2/kg biochar at optimal pyrolysis), and cost considerations. Finally, challenges and research gaps are identified (e.g., standardizing PKSB quality, long-term durability, scale-up costs), and future research directions are proposed.

Keywords: *Palm kernel shell biochar; supplementary cementitious material; response surface methodology; optimization; cement mortar; sustainability; carbon sequestration.*

1.0 Introduction

Cement is the most widely used construction material, with global production ≈4.3 billion t/year. However, conventional Portland cement has a huge carbon footprint – accounting for about 8% of world CO_2 emissions (process + fuel emissions) – and its demand is rising with population growth and infrastructure needs (Adisa et al., 2026; Çakmak et al., 2025). For perspective, in 2022 cement manufacture emitted approx. 1.6 GtCO_2 (≈8% of the global total) (Andersen & Geels, 2023). As a result, "clinker" reduction strategies, which involve replacing high emission clinker with alternative materials, are key to decarbonizing concrete. One promising route is incorporating supplementary cementitious materials (SCMs), typically industrial or agricultural by products that react pozzolanically or act as inert fillers, thereby reducing clinker demand (Abdulwahab et al., 2021; Odeyemi et al., 2021, 2025). Classic SCMs include fly ash, ground granulated blast furnace slag, silica fume, volcanic ash, and calcined clays. These materials have been shown to improve concrete properties and durability (Adisa et al., 2025; Akinpelu et al., 2026). For example, Ahmad et al. (Ahmad et al., 2022) found that silica fume enhances strength and reduces shrinkage. However, some SCMs, such as fly ash, are declining because of coal phase out policies, while others, such as calcined clays, require additional processing (Tian et al., 2025). Consequently, there is active research into novel SCMs derived from waste streams. In parallel, biochar, a stable carbonaceous material produced from biomass pyrolysis, has gained attention as a multifunctional additive in cementitious materials. Biochar's porous structure and carbon content can enhance the mechanical and thermal performance of concrete, sequester carbon, and recycle agricultural residues (Maddala et al., 2025; Pudełko et al., 2021; Senadheera et al., 2023).

Studies have shown that biochar can improve strength and durability while reducing the thermal conductivity of concrete. Moreover, because biochar is derived from biomass, often agricultural waste, its use in concrete offers dual climate benefits: first, replacing cement or clinker lowers CO_2 emissions, and second, storing stable carbon within the material keeps CO_2 out of the atmosphere (Odeyemi et al., 2025). Consequently, biochar concrete is considered a promising carbon negative or low carbon construction material. Palm kernel shell (PKS) is a key candidate biochar feedstock in tropical regions. Palm oil production generates ~70–80 million t/year of solid waste (empty fruit bunches, shells, fiber, etc.), with PKS being a major

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fraction. Malaysia (second-largest producer) exported ~1 million t of PKS in 2020. Typically burnt for energy or disposed, PKS is rich in lignocellulose and has a high fixed-carbon potential. Thermal conversion (slow pyrolysis) yields ~30–50% biochar by mass with very high carbon content. Recent work shows that PKS biochar (PKSB) has <0.5% silica and acts mainly as a carbonaceous filler rather than a classical pozzolan, but still can improve concrete by filler and nucleation effects. Notably, Subramaniam et al. (2026) optimized PKSB pyrolysis and reported yields ~38.2% with 73% C, while Okokpujie et al. (2023) found ~41% yield and 53–59% fixed C. Such high-C char not only aids concrete strength, but also sequesters CO_2. In fact, Aman's work estimated ~14.4 kg CO_2 captured per kg PKSB at optimal pyrolysis.

Response Surface Methodology (RSM) is a statistical optimization technique widely used in chemical and materials engineering. RSM combines designed experiments (e.g. central composite design) with regression modeling to identify the influence of process variables and find optimum conditions. In the context of cement and biochar, RSM has proven effective to optimize mix designs and pyrolysis parameters with relatively few experiments. For example, recent studies applied RSM to biochar particle size and content in mortar, and to PKSB pyrolysis (this review's focus). RSM yields quadratic models whose significance is tested by ANOVA, yielding high R^2 and low p-values when valid. Key metrics include the coefficient of determination (R^2, adj. R^2), p-values (<0.05), lack-of-fit tests, and adequate precision (signal-to-noise >4) (Onokwai et al., 2023; Xie et al., 2025). This review will cover these RSM principles and survey their application to PKSB optimization.

This article provides a thorough, up-to-date review of PKS biochar as an SCM and its optimization via RSM. Section 2 overviews common SCMs and introduces PKSB context. Section 3 describes PKSB production methods and material properties (thermochemical parameters, yield, composition). Section 4 reviews its physicochemical and (potential) pozzolanic characteristics. Section 5 examines the use of PKSB in cementitious systems, covering fresh concrete behavior, mechanical and durability performance, and microstructural observations. Section 6 presents RSM fundamentals (designs and statistics) and how RSM has been used in cementitious research. Section 7 synthesizes RSM studies specifically on PKSB (with a comparative table of design, variables, findings). Section 8 assesses environmental and economic aspects (LCA, CO_2 footprint, cost factors). Finally, Sections 9–10 identify challenges, research gaps and future directions, concluding with key takeaways.

Biochar's general suitability as an additive has been reviewed before — notably by Nahuat-Sansores et al. (2022), who proposed a compositional framework (C/Si ratio, O/C ratio, alkali content, surface functional groups) applicable across feedstocks. However, no review has focused specifically on palm kernel shell biochar (PKSB). Prior PKS-related work has centered on palm kernel shell ash (PKSA), a combustion product evaluated mainly for residual silica and pozzolanic behavior, whereas PKSB — a pyrolysis product that behaves largely as a carbonaceous filler rather than a pozzolan — has rarely been treated as a distinct material. This review fills that gap by consolidating PKSB-specific production, characterization, and application literature, and by linking it for the first time to the parallel body of work using RSM to optimize PKSB's pyrolysis and mix-design parameters.

Existing literature splits into two groups: broad biochar-as-SCM reviews that give general frameworks but no PKS-specific depth or process optimization (Nahuat-Sansores et al., 2022), and individual PKS/PKSB studies that report production or performance data in isolation, without cross-study synthesis (Onokwai et al., 2023; Aman et al., 2023; Zhou et al., 2023). Neither connects production optimization to downstream cementitious performance. This review does so directly, synthesizing PKSB production, physicochemical properties, cementitious performance, and RSM optimization studies (Section 7) within one comparative framework, surfacing trends and gaps that isolated studies could not. Because PKS, PKSA, PKSB, biochar, ash, and SCM are all discussed and easily conflated, a schematic figure has been added showing the two processing routes from raw PKS — combustion to PKSA versus slow pyrolysis to PKSB — alongside the differing properties each route produces (carbon content, residual silica, porosity, reactivity mechanism). This gives readers one clear reference point before the materials are discussed individually in Sections 2–4.

2.0 Literature Review

SCMs are aluminosilicate or carbon-based materials that partially replace Portland cement in concrete, improving sustainability and often enhancing properties (Adisa et al., 2025). Common SCMs include silica fume, fly ash, slag, calcined clays, and natural pozzolans. They can act as pozzolans (reacting with $Ca(OH)_2$ to form C–S–H), inert fillers, or both. For example, fly ash (a coal-combustion by-product) and slag are industrial waste SCMs that are extensively used. Silica fume (from Si-metal production) is a highly reactive SCM that significantly increases strength and durability. Calcined clays (e.g. metakaolin) and volcanic ashes are also effective SCMs with high pozzolanic SiO_2 (Akinpelu et al., 2026; Becerra-Duitama & Rojas-Avellaneda, 2022; Wilson et al., 2026). A recent review listed many non-traditional SCMs: rice husk ash, wood waste

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biochar, natural pozzolans, etc. Incorporating these reduces cement clinker content (and hence CO_2) and can improve strength or durability (depending on reactivity and particle packing) (Miranda et al., 2026).

Biochar can serve a dual role: (a) as a carbonaceous filler and micro-aggregate, and (b) as a carbon sink. Unlike reactive SCMs, biochars often have low reactive silica, but their high surface area and porosity can refine concrete microstructure. Reviews note biochar can improve concrete compressive strength and durability at low dosages (1–3% by mass). For example, Zhou et al. (2023) found 1% biochar increased mortar strength by ~10%, whereas higher (>5–8%) reduced strength. Biochar also tends to reduce workability because of water absorption. Yaseen et al. (2024) provided one of the most comprehensive recent treatments of SCM performance over time, examining how ternary blends of fly ash, silica fume, and nanosilica evolve in compressive strength across curing ages while simultaneously conducting a life cycle assessment of environmental impacts. Their finding that an 80% cement blend with 5% fly ash, 10% silica fume, and 5% nanosilica produced both higher strength parameters and an improved microstructure demonstrated that carefully optimized SCM combinations can substantially reduce clinker content without structural compromise. This work is significant because it frames SCM research not merely as a materials science problem but as an integrated sustainability question, requiring trade-offs between strength, durability, cost, and carbon footprint — Armaghani & Cavalline (2025) published a reference survey of SCM use in US concrete practice, providing detailed benchmarks for fly ash, slag, silica fume, and natural pozzolans. The report highlighted silica fume's extreme reactivity — stemming from its very high amorphous SiO_2 content of at least 85% and ultra-fine particles averaging 0.1–0.5 µm — as the upper benchmark of pozzolanic performance, against which lower-reactivity materials like PKSB must be honestly compared.

Palm Kernel Shell as carbonaceous filler: In waste valorization efforts, PKS (a palm oil mill by-product) has been studied in concrete mainly as coarse aggregate, but recent work explores its ash or biochar as SCM. PKS ash has some silica and has been used up to ~20% cement replacement, usually lowering strength. Pyrolyzed PKS (biochar) is less studied but promising. PKSB generally contains mostly carbon (60–80%) with small amounts of silica, potassium, etc (Sambogha et al., 2025). Thus, it behaves more like a carbon microfiller than a reactive pozzolan. Its benefits in concrete come from internal curing, microfilling, and possibly some mineral interactions. For example, biochar's oxygen-containing surface groups can bind Ca^{2+} and nucleate C–S–H. The literature on biochar as an SCM has grown rapidly since approximately 2020 and now constitutes a distinct sub-field. Zhao et al. (2024) assessed how biochar addition affects 7- and 28-day compressive strength of Portland cement composites.

The study found that plant-based biochars (excluding rice straw and hardwood) improved 28-day compressive strength by 3–13%, with optimal performance achieved at pyrolysis temperatures above 450°C and heating rates of approximately 10°C/min. Feedstock type, pyrolysis conditions, pre-treatment, dosage, and curing regime all significantly influenced outcomes. This meta-analytic evidence supports the document's assertion that biochar can improve concrete compressive strength at low dosages, while also clarifying that these benefits are highly conditional on production parameters — a finding of direct relevance to PKSB, whose properties are similarly sensitive to pyrolysis conditions. Reinforcing this, Mahi et al. (2025) synthesized experimental findings across numerous biochar-concrete studies, reporting that up to 2% cement replacement can increase early-age compressive strength by as much as 40%, while doses exceeding 5% diminish strength due to increased porosity and elevated water demand. Flexural strength gains were also documented, particularly with pre-soaked biochar, suggesting that internal curing — a mechanism enabled by biochar's high water absorption capacity — is a key contributor to early-age strength gains.

The critical review by Nahuat-Sansores et al. (2022) on biochar suitability as an SCM or filler established a detailed framework for evaluating biochar quality, proposing that carbon-to-silicon ratio, oxygen-to-carbon ratio, alkali and alkaline metal content, chloride content, and carboxylic and alkyne surface functional groups are the key parameters governing performance. Biochars with reactive functional groups such as C=C and COOH were identified as potential concrete accelerators capable of speeding up hydration and reducing construction timelines, while those with high chloride content were flagged as problematic for steel corrosion. This framework is directly applicable to PKSB evaluation, where low silica, moderate potassium, and oxygen-bearing surface groups collectively define a material that is unlikely to function as a classical pozzolan but may contribute through surface chemistry and filler mechanisms. Ali et al. (2023) further demonstrated these mechanisms through thermo-physical and microstructural characterization of biochar-incorporated cementitious material, confirming that biochar's low thermal conductivity introduces modest thermal insulation benefits, while SEM imaging revealed a heterogeneous pore structure that modifies heat transport in the cement matrix. Figure 1 presents a schematic of the two processing routes from raw palm kernel shell — combustion to PKS ash (PKSA) and slow pyrolysis to PKS biochar (PKSB) — together with the differing material properties each route produces.

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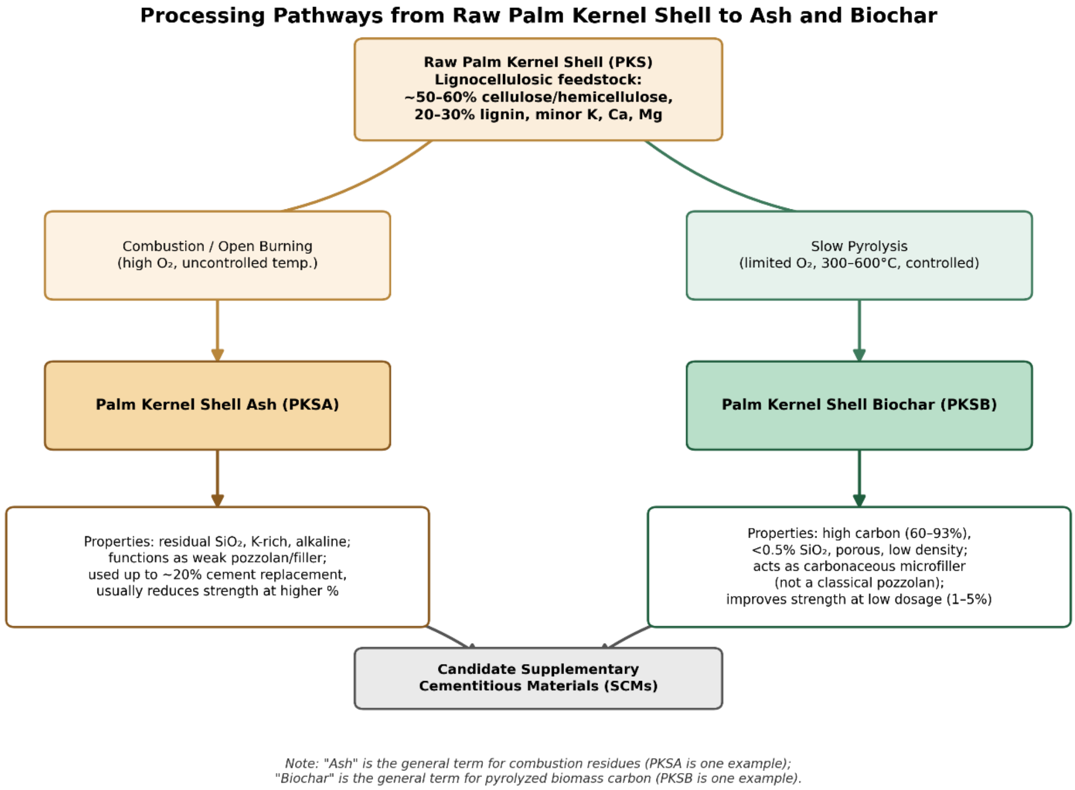

Figure 1: Processing pathways from raw palm kernel shell to ash (PKSA) and biochar (PKSB), showing the differing material properties resulting from each route

3.0 Materials and Methods

3.1 Review Design and Scope

This article is a narrative, comprehensive review rather than a systematic review or meta-analysis; its objective is to synthesize the fragmented literature on palm kernel shell biochar (PKSB) as a cementitious additive and to link, for the first time, PKSB production optimization to its downstream performance in cement and mortar systems via Response Surface Methodology (RSM). The scope was deliberately bounded to studies addressing (i) palm kernel shell (PKS) as a feedstock for biochar or ash, (ii) biochar/PKSB use in cementitious systems, and (iii) RSM applied to either pyrolysis optimization or cementitious mix design involving biochar. Broader biochar-in-concrete literature was included selectively, where PKSB-specific data were unavailable, to provide comparative context — this is flagged explicitly wherever findings are extrapolated from non-PKS feedstocks rather than PKSB itself.

3.2 Literature Search Strategy

Peer-reviewed journal articles, theses, and conference papers were identified through Scopus, Web of Science, ScienceDirect, and Google Scholar, supplemented by forward and backward citation searching (snowballing) from key sources such as Aman et al. (2023), Onokwai et al. (2023), and Nahuat-Sansores et al. (2022). Search terms combined the following clusters using Boolean operators: (a) feedstock terms — "palm kernel shell," "PKS," "oil palm waste"; (b) material terms — "biochar," "pyrolysis," "ash," "carbonaceous filler," "supplementary cementitious material," "SCM"; (c) application terms — "cement," "concrete," "mortar," "compressive strength," "durability," "microstructure"; and (d) methodology terms — "response surface methodology," "RSM," "Box–Behnken," "central composite design," "optimization," "ANOVA." No lower date bound was imposed, but searches emphasized publications from 2012 onward, with particular weight given to the 2020–2026 window, reflecting the rapid growth of biochar-as-SCM research over this period.

3.3 Inclusion and Exclusion Criteria

Studies were included if they reported primary data or original analysis on PKS/PKSB production, physicochemical characterization, or performance in cementitious matrices, or if they applied RSM to biochar pyrolysis or biochar-modified mix design. Studies were excluded if they addressed unrelated biomass wastes without transferable relevance, duplicated data already captured from a primary source, or were not accessible in full text. Where evidence specific to PKSB was sparse (e.g., long-term durability, cost data), closely related biochar or PKS-ash studies were retained but explicitly distinguished from PKSB-specific findings in the text.

3.4 Data Extraction and Synthesis

For studies involving RSM (synthesized in Table 6), the following were extracted where reported: experimental design type (CCD, BBD, Doehlert), independent variables and their ranges, response variables, optimum conditions, model statistics (R^2, adjusted R^2, p-values, lack-of-fit, adequate precision), and principal findings. For characterization and performance studies (Tables 1–5), extracted data included proximate/ultimate analysis, physical and pozzolanic properties, fresh-state behavior, mechanical strength outcomes, and durability/microstructural findings, with dosage and testing conditions recorded to allow cross-study comparison. Findings were synthesized thematically (production, physicochemical properties, application performance, RSM optimization, environmental/economic assessment) rather than through meta-analytic pooling, given the heterogeneity of mix designs, feedstocks, and testing protocols across the included studies.

3.5 Quality Appraisal of RSM Studies

RSM studies were assessed for statistical validity using the diagnostic criteria detailed in Section 6.2 — $R^2 \geq 0.90$, agreement between adjusted and predicted R^2 (difference < 0.20), model term significance ($p < 0.05$), a non-significant lack-of-fit test ($p > 0.05$), and adequate precision > 4.0. This framework was applied consistently when evaluating and comparing the RSM studies summarized in Table 6, and is noted as a limitation where source studies did not report all diagnostic statistics.

4.0 Results and discussion

4.1 Palm Kernel Shell Biochar: Production and Properties

Feedstock and Pretreatment: Palm kernel shells are the hard endocarps left after removing oil palm kernels. They are lignocellulosic (~50–60% cellulose/hemicellulose, 20–30% lignin) with minor minerals (K, Ca, Mg). Raw PKS waste is often crushed and dried before pyrolysis (Onokwai et al., 2023). Schematic flowchart of palm kernel shell biochar (PKSB) production via slow pyrolysis in concrete is shown in Figure 2.

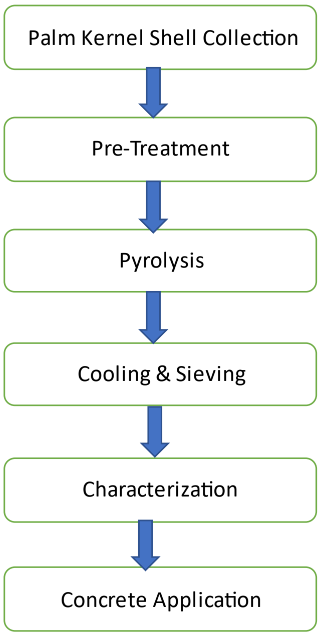

Figure 2: Schematic flowchart of palm kernel shell biochar (PKSB) production

The foundational optimization study for PKSB as a cementitious material was published by Aman et al. (2023) using response surface methodology (RSM) based on a Box–Behnken design to identify the pyrolysis conditions — temperature, heating rate, and residence time — that simultaneously optimized biochar yield, carbon content, oxygen content, silica content, and potassium content for cementitious use. The study identified 409°C, 15°C/min, and 120 min under N_2 as optimal conditions, yielding 38.2% biochar with 73.37% carbon, 25.48% oxygen, 0.44% silica, and 0.39% potassium. Temperature and residence time were confirmed

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as the most influential factors, with the carbon content of the biochar found to be directly proportional to pyrolysis temperature. This study is particularly important because it was the first to explicitly frame PKSB production optimization around cementitious use criteria, targeting properties known to be beneficial in the cement matrix — namely high carbon, moderate potassium for alkaline activation, and minimum oxygen. It established a methodological template followed by subsequent studies in this area. Complementing this, Onokwai et al. (2023) applied RSM to optimize five pyrolysis parameters simultaneously — temperature, residence time, heating rate, N_2 flow rate, and particle size — for PKS biochar production, achieving an optimal yield of 40.5 wt% at 357°C, 6.5 min, 12.8°C/min, 25 cm^3/min N_2, and 0.9 mm particle size. SEM/EDX analysis confirmed that the resulting biochar had a heterogeneous, porous morphology with detectable inorganic elements including carbon, calcium, oxygen, silicon, potassium, aluminum, and magnesium. The study's findings reinforced the principle that lower pyrolysis temperatures tend to maximize yield at some cost to carbon purity, while higher temperatures favor carbon enrichment at the expense of mass recovery. At the extreme high-temperature end of the production spectrum,

Beyond the studies specifically targeting cementitious optimization, several broader pyrolysis investigations have characterized PKS biochar's fundamental properties across a range of conditions. Azman et al. (2022) conducted a comprehensive slow pyrolysis study of both PKS and empty fruit bunch (EFB) wastes, using RSM to simultaneously optimize biochar yield and higher heating value (HHV). Under optimal conditions of 500–504°C with 18.9–20°C/min heating and 30 mL/min N_2 flow, PKS-biochar achieved 36.86 wt% yield with 67.58% carbon and an HHV of 28.96 MJ/kg — an energy density comparable to coal. This study is significant for several reasons: it confirms that PKS-biochar consistently falls within the 30–50% yield range documented in the broader literature, that carbon contents in the 60–70% range are achievable at moderate temperatures, and that the material has substantial energy content that must be considered if high-temperature curing or autoclaving is involved in concrete production. The slow pyrolysis optimization study by Oyebanji et al. (2023) using a Box–Behnken design similarly found that PKS pyrolysis at 500°C with 2 L/min N_2 and 750 μm particle size produced the highest yield of 44.91 wt% — among the highest in the published literature — while the resulting biochar demonstrated a CO_2 adsorption capacity of 0.46 mmol/g, quantifying its carbon capture functionality beyond the concrete context. Setiawan et al. (2025) found that slow pyrolysis at 400–600°C for 30–90 min consistently produces PKS-biochar within the 33–52% yield range, which the authors identified as the conditions most favorable for soil and construction applications. This synthesis provides a practical window for industrial PKSB production, centered on the 400–600°C temperature range that balances yield, carbon content, and energy input.

The physical properties of PKSB — particularly its surface area, porosity, and particle size distribution — are critical determinants of its performance in cement matrices. Studies on biochar produced from various feedstocks have documented BET surface areas in the range of 300–600 m^2/g for finely ground biochar, with specific PKSB studies confirming surface areas in this range when biochar is milled to below 100 μm. The highly porous morphology of PKSB, observed consistently across SEM analyses in Aman et al. (2022), Onokwai et al. (2023), and Thuwala et al. (2020), arises from the volatilization of cellulose and hemicellulose during pyrolysis, which leaves behind an aromatic carbon skeleton riddled with micro- and mesopores. SEM micrograph of Palm kernel shell after pyrolysis in Figure 3 shows this porosity has a dual effect in concrete: on one hand, it provides a high surface area that can interact with cement hydration products, particularly Ca^{2+} ions that can be adsorbed and potentially nucleate C–S–H on the biochar surface; on the other hand, it creates a strong water absorption capacity that reduces fresh concrete workability at higher dosages, a challenge documented across the broader biochar-concrete literature.

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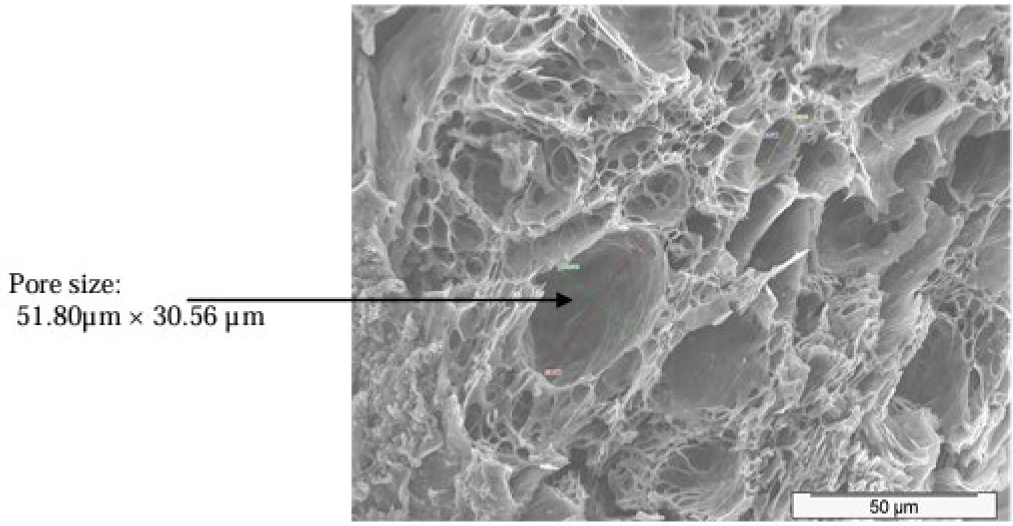

Figure 3: SEM micrograph of Palm kernel shell after pyrolysis (Edmund et al., 2014)

The chemical composition of PKSB has been consistently documented across multiple studies as predominantly carbon (50–93% depending on pyrolysis temperature), with small but potentially significant quantities of oxygen (as functional groups), potassium, calcium, and silicon. The FTIR spectra reported in Aman et al. (2022) and related studies show persistent O–H, C=O, and C–O functional groups reflecting residual lignin-cellulose structures that survive pyrolysis, particularly at lower temperatures. The characterization framework proposed by Nahuat-Sansores et al. (2022) — using carbon-to-silicon ratio, oxygen-to-carbon ratio, and surface functional group profiles to assess biochar suitability as SCM — aligns well with PKSB's profile: high carbon-to-silicon ratio (indicative of a filler rather than pozzolan), moderate oxygen content (supporting surface reactivity), and the presence of carboxyl and hydroxyl groups that interact with calcium ions.

The implications of PKSB's chemical composition for pozzolanic reactivity were examined in the context of palm kernel shell ash (PKSA) by Olutoge et al. (2012), who found that 10% PKSA replacement yielded 22.8 N/mm^2 compressive strength at 28 days — satisfactory but below the OPC control. This early study, while dealing with ash rather than pyrolytic biochar, established the baseline behavior of PKS-derived cementitious materials: useful as partial replacements at low dosages, but lacking the reactivity to match conventional SCMs in strength development. This baseline was updated by Ortega et al. (2025), which optimized combustion conditions to maximize amorphous SiO_2 content and found that controlled incineration produced a meaningfully more pozzolanic material than uncontrolled burning — underscoring that the processing pathway (incineration versus pyrolysis) fundamentally determines whether a PKS-derived material behaves as a pozzolan or as a carbon filler. PKSB, produced through pyrolysis rather than incineration, retains its carbon content at the expense of reactive silica, placing it firmly in the filler category and distinguishing it from PKSA produced at high incineration temperatures. Jabar et al. (2025) noted that variable silica content, water absorption, and workability reduction are the key challenges for PKSB specifically, and that its most productive application is likely at low dosages (1–5%) in complementary blends with reactive SCMs — consistent with the broader biochar-concrete literature. The use of PKSB as a carbon sink and climate intervention tool, beyond its functional role in concrete, was articulated by Baskar & Nivethitha (2026), who argued that biochar's recalcitrant carbon matrix sequesters biogenic CO_2 within the built environment for decades, and by Mekky et al. (2024), whose LCA quantified a 5–15% reduction in global warming potential for biochar-concrete relative to conventional OPC concrete. For PKSB specifically — produced from a palm oil by-product that would otherwise be incinerated or left to decompose — the net carbon benefit is particularly strong, because the carbon sequestered in the biochar represents emissions avoided from both cement production and waste decomposition simultaneously. Table 1 provides a comprehensive evaluation of the material's fuel potential, thermal stability, and structural breakdown.

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Table 1: Characteristics of produced biochar from PKS (Onokwai et al., 2023)

Category	Analysis	Weight %
Proximate analysis (wt%)	Moisture contents	0.30 ± 0.01
Proximate analysis (wt%)	Volatile matter	73.70 ± 0.40
Proximate analysis (wt%)	Fixed carbon	22.50 ± 0.21
Proximate analysis (wt%)	Ash	3.50 ± 0.02
Ultimate analysis (wt%)	Carbon	48.90 ± 1.14
Ultimate analysis (wt%)	Hydrogen	5.38 ± 0.01
Ultimate analysis (wt%)	Nitrogen	0.22 ± 0.01
Ultimate analysis (wt%)	Oxygen	45.03 ± 0.13
Ultimate analysis (wt%)	Sulphur	0.03 ± 0.001
Structural composition analysis (wt%)	Cellulose	28.92 ± 0.13
Structural composition analysis (wt%)	Hemicellulose	25.01 ± 0.12
Structural composition analysis (wt%)	Lignin	45.41 ± 0.42
Heating value analysis (MJ/kg)	HHV	19.98 ± 0.43
Heating value analysis (MJ/kg)	LHV	18.70 ± 0.21

Note that Onokwai et al. (2023) features a low-temperature, short-residence batch process (357 °C for 6.5 minutes), which explains the relatively high oxygen and volatile matter content. In contrast, optimized long-duration slow pyrolysis conditions, as referenced in Aman et al. (2022), concentrate carbon content above 70% while significantly reducing oxygen levels, producing a more stable and carbon-rich biochar.

4.2 Physicochemical and Pozzolanic Characteristics of PKS Biochar

Mineralogy and Amorphous Content: Because PKSB is mostly carbonaceous, it is largely amorphous with only trace minerals. XRD analysis of PKSB typically shows a broad hump (amorphous carbon) and weak peaks for quartz or calcite if any. For example, Zhou et al. (2023) note no significant crystalline silica in BC XRD (their BC was from mixed waste). Similarly, PKSB often shows minor $CaCO_3$ or KCl phases from ash impurities. Overall, PKSB lacks the reactive aluminosilicates of fly ash or slag, so its pozzolanic reactivity (reaction with $Ca(OH)_2$) is low.

Surface Chemistry: PKSB's surface bears oxygen-containing groups (–OH, –COOH, etc.) inherited from biomass. FTIR spectra (Onokwai et al.) reveal O–H (3200–3500 cm^{-1}), C–H (2900 cm^{-1}), C=O/C=C (1600 cm^{-1}), and C–O (1000 cm^{-1}) bands. These polar groups can interact with cement phases. For instance, carboxyl and hydroxyl on PKSB can chelate Ca^{2+}, effectively promoting nucleation of calcium-silicate-hydrate (C–S–H) gels (Onokwai et al., 2023). SEM images (Zhou et al.) of cement with PKSB (at 2.7% content) in Figure 4 show PKSB particles decorated with C–S–H crystals in their pores, indicating that hydration products grow on or into PKSB. This suggests PKSB can act as a nucleation site for hydration (seed effect).

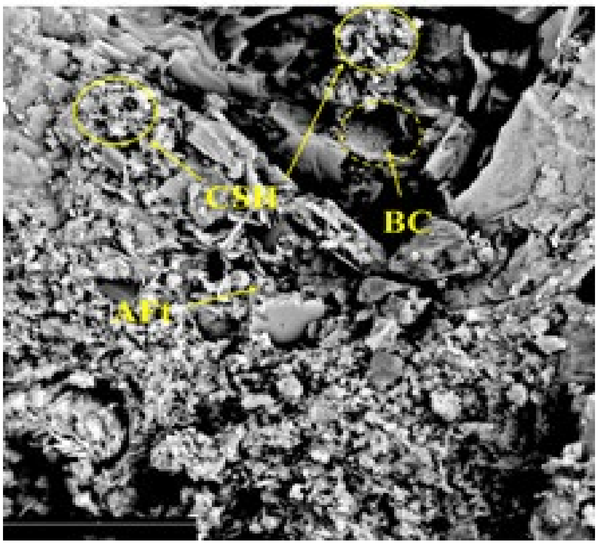

Figure 4: SEM image of 2.7% content PKSB in concrete (Zhou et al., 2023)

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Pozzolanic Reactivity: True pozzolanic reactivity requires appreciable amorphous silica/alumina. PKSB's SiO_2 content (<0.5%) is negligible, so it does not consume $Ca(OH)_2$ the way rice husk ash or fly ash does (Elyasigorji et al., 2023). Studies confirm little CH-consumption effect. However, PKSB's high carbon surface area can physically adsorb $Ca(OH)_2$ or other ions. In mixtures with 1–5% PKSB, any minor strengthening appears due to physical effects (pore filling, refinement of ITZ) rather than chemical bonding (Ali et al., 2023; Mahi et al., 2025; Nahuat-Sansores et al., 2022; Zhao et al., 2024).
Thermal and Electrical Properties: PKSB's thermal conductivity (~0.1–0.2 W/m·K) is much lower than cement (0.8 W/m·K), so small PKSB additions can slightly improve concrete insulation (Park et al., 2021). It also conducts electricity poorly (being carbon), which can be a concern for durability (carbon black accelerates steel corrosion, though PKSB levels are low) (Park et al., 2025).
Other Properties: PKSB is chemically stable and exhibits negligible biodegradability. It has a high pH (>10) when water is passed through, indicating alkalinity from ash. In mix, PKSB absorbs water, requiring adjustments (e.g. extra water or superplasticizer) for workability. The modest alkali content (K_2O ~0.4%) can mildly accelerate early hydration (Saccani et al., 2025). Table 2 shows the Physical properties and pozzolanic properties of Palm Kernel shell biochar.

Table 2: Physical properties and pozzolanic properties of Palm Kernel shell biochar

Physical & Surface Properties			
BET Surface Area	106 (raw) → 329 m^2/g	600 °C, 60 min	Large surface area enhances adsorption capacity and pozzolanic reactivity (Kong et al., 2019)
Total Pore Volume	0.01 → 0.31 cm^3/g	600 °C	Pore development increases with temperature; supports water retention (Kong et al., 2019)
Biochar Yield	~38.2 % (optimized)	409 °C, 120 min	Yield decreases with higher temperature; trade-off between quality and quantity (Ma et al., 2017)
Water Holding Capacity	2.23 → 6.21 g(H_2O)/10 g	500 °C, 30 min	Improved WHC beneficial for soil amendment (Kong et al., 2019)
Specific Gravity	< 2.0	—	Lower than OPC (~3.15); improves workability in concrete mixtures (Fapohunda et al., 2021)
Chemical & Pozzolanic Reactivity			
pH	9.3 – 12.0	400–600 °C	Alkaline nature beneficial for cement hydration and liming of acidic soils (Kong et al., 2019)
Cation Exchange Capacity (CEC)	3.00 – 4.44 cmol/kg	400 °C, 60 min	Higher at lower temperatures; good for nutrient retention in soil
Optimal Cement Replacement	10 – 20 %	28-day cure	10% replacement achieved good compressive strength; 20% often optimal (Olutoge et al., 2012)
Carbon Sequestration Potential	0.63 kg CO_2 / kg PKS	500 °C, 90 min	Highest at moderate temperature; stable aromatic carbon resists decomposition
Optimal Pyrolysis Temperature	400 – 600 °C	Slow pyrolysis	Completes cellulose/hemicellulose decomposition while maximizing surface area and fixed carbon (Okoroigwe & Saffron, 2012)

Essentially, PKSB's physicochemical profile is characterized by high carbon (>70%) and porosity, low mineral content, and reactive surface groups. It provides physical filler and nucleation effects in cement but limited true pozzolanicity. Its role is more akin to a porous carbon microfiller that enhances composite packing and sequesters carbon, rather than a cementitious binder. The following section examines how these traits translate into performance in cement composites. Given this profile, PKSB is best classified not as a true SCM in the classical sense — which implies pozzolanic reaction with $Ca(OH)_2$, as with fly ash or silica fume — but as a multifunctional cementitious additive combining carbonaceous micro-filler and nucleation-seeding functions with negligible pozzolanic contribution. Its performance benefits (pore refinement, ITZ densification, C–S–H nucleation) are physical and surface-chemical rather than chemical-reactive, distinguishing it from reactive SCMs and aligning it more closely with inert or semi-active fillers. This distinction matters for interpreting the mechanical and durability results discussed below: apparent "cement

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replacement" benefits at low dosages reflect packing and nucleation effects, not clinker-equivalent binding capacity, and PKSB should not be assumed to scale like a reactive pozzolan at higher replacement levels.

4.3 Properties of PKS Biochar concrete

Fresh Properties: Adding PKS biochar to concrete or mortar mixes generally reduces workability (Table 3). Biochar's porous, carbon-rich structure strongly absorbs water, lowering the slump. For example, Patel et al. (2025) observed dramatic slump reduction at 5% biochar, and recommended admixtures if used above ~1%. Similarly, general biochar-mortar studies report that each percent of biochar can reduce slump by ~1–2 cm. PKSB's high surface area exacerbates this. Designers must account for higher water demand or use superplasticizers when substituting PKSB for cement. PKSB also slightly increases mixing viscosity. Importantly, low-dosage (≤3%) PKSB still yields workable mixes, while high doses (≥5%) risk poor consistency and compaction. No published work has found unexpected adverse chemical interactions in the fresh state, apart from this physical water demand. All studies in Table 3 agree that biochar reduces workability due to its porous carbon structure absorbing mix water. Increasing biochar dosage in cement pastes reduces setting time and increases water demand irrespective of biochar type, with a nearly linear decline in workability and density observed as biochar replacement dosage increases. The practical fix is pre-soaking biochar before mixing or using superplasticizers at dosages above 1–2%.

Table 3: Effect of PKSB on Fresh properties

Study	Biochar Type	Dosage Tested	Workability Finding	Mechanism Noted	Recommendation
Aman et al. (2023)	PKS biochar (409 °C)	Optimized SCM mix	Higher water demand at increased dosage	Porous carbon structure acts as internal sponge (absorbs mix water)	Use superplasticizer
Zhou et al. (2023)	Agricultural biochar (~51 μm)	1 – 5 %	Slump declines nearly linearly; manageable at ≤3%	High BET surface area increases water absorption	≤3% is feasible
Maljaee et al. (2021)	Various biochars (review)	0 – 10 %	Each 1% BC reduces slump by ~1–2 cm; ≥5% risks poor compaction	Carbon porosity and high surface area dominate water demand	Use admixture if >1%
Sirico et al. (2021) – UHPC	Palm / date / peach shells BC	0.1 – 24 %	Nearly linear decline in workability and density	Biochar absorbs superplasticizer and mix water	1% optimum for UHPC
Gupta et al. (2021)	Wood biochar	1 – 5 %	Water demand increases	Pre-soaking saturates biochar pores	Pre-soak BC if dosage >2%

Although the studies in Table 3 agree that PKSB reduces workability, the reported magnitude varies with mix design (w/b ratio, use of superplasticizers), material characteristics (particle size and porosity, which differ by pyrolysis condition), and testing conditions (pre-soaked vs. dry addition, slump vs. flow-table methods). A key limitation is that much of the evidence is extrapolated from non-PKS biochars rather than PKSB itself, so quantitative comparisons across studies remain unreliable pending standardized, PKSB-specific testing.

Mechanical Properties: Numerous studies (mostly on other biochars) show that small PKSB replacements (≈1–5%) can increase or maintain compressive strength relative to plain cement, while larger amounts (>5–8%) generally decrease strength. This follows a parabolic trend. A key mechanism is internal curing and microfilling: fine PKSB particles fill voids and refine porosity, and provide extra surface for C–S–H growth. RSM-based mortar tests by Zhou et al. (2023) found optimum ~2.7% biochar (51 μm) gave ~10% higher 28-day strength over control. They noted 1% biochar gave ~+10% strength compared to no-biochar. In practice, PKSB up to ~3–4% rarely harms strength and often boosts it slightly. For instance, Aman's PhD found 4% PKSB gave maximum strength gain in concrete. However, excessive PKSB has a dilutive effect: replacing too

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much cement reduces clinker content and increases porosity (PKSB cannot bind like cement). Studies show 5–10% biochar replacements cut strength by ~10–20%, and 8% led to ~50% reduction (Fahmy et al., 2020; Lee et al., 2017; Lua, 2025; Sirico et al., 2020). The brittle, irregular PKSB particles also weaken the matrix if overused. Thus, optimal dosage is low. In all cases, adequate curing is important; PKSB's carbon surface may require more complete hydration of the remaining cement to compensate for its inertness. The optimal combination for enhancing mechanical performance is achieved when biochar particles have a median diameter of ~51 µm and a content of ~2.69% of the mixture (Table 4). At the broader scale, biochars from plant-based feedstocks improved 28-day compressive strength by 3–13%, with pyrolysis temperatures above 450 °C and small particle sizes giving the best results. Dosages below 2.5% of binder weight consistently enhanced compressive strength. Beyond ~5–10%, the dilution effect reverses all gains.

Table 4: Mechanical properties of PKSB concrete

Study	Biochar Type	Optimum Dosage	Compressive Strength Outcome	Flexural / Tensile Outcome	Key Mechanism / Notes
Zhou et al. (2023)	Agri BC (~51 µm)	2.69%	~10% higher 28-day CS vs. control at optimum	~10% higher flexural strength at 3% BC	RSM optimized; BC acts as nucleation site for C-S-H, densifies ITZ
Zhang et al. (2024)	Plant-based feedstocks (606 obs.)	< 2.5 %	+3–13% 28-day CS for most plant biochars	Not reported (CS focused)	Pyrolysis >450 °C most effective; small particles outperform coarse
Aman et al. (2023/2024)	PKS biochar (409 °C)	~4 %	4% PKSB + 5% EFB: maximum 28-day strength	Shrinkage reduced ~10% at optimum	Binary PKS+EFB system effective; pure PKSB shows parabolic trend
Kua et al. / Gupta et al. (2018; 2021)	Wood biochar (pre-soaked)	2 – 3 %	+18.95% compressive at 2% BC	+19.64% splitting tensile & +12% flexural at 2% BC	Internal curing via porous BC; pre-soaking enhances performance
Sirico et al. (2025)	Palm shell BC	1%	Peak CS at 1% (+2.65% over control)	Not reported	Minimal porosity at 1%; high BC (24%) causes strength loss due to unfilled pores
Liu et al. (2022)	Bamboo biochar	1 – 3 %	Increased CS and initial crack resistance	Improved toughness; crack bridging observed	Rough BC surface provides modest bonding and tensile stress transfer
Mahi et al. (2025)	Multiple feedstocks	Max 5 %	5–10% BC reduces CS by ~10–20%; ≥8% can reduce ~50%	Flexural strength mirrors compressive trend	Dilution effect dominant above 5% without co-SCMs

Reported optimum PKSB dosages range from roughly 1% to 5%, largely because curing regime, water-to-binder ratio, SCM type, and particle fineness all shift the balance between beneficial microfilling and detrimental dilution. Longer curing and finer particles tend to favor higher optimum dosages, while shorter curing or coarser biochar lowers it. Since most studies test only a narrow dosage range around their own assumed optimum rather than a shared mix design, the reported "optimum" is better understood as mix-specific than universal.

Durability and Microstructure: PKSB generally enhances durability metrics at low dosage. Its filler action reduces permeability and refines the interfacial transition zone (ITZ) between paste and aggregates. Studies with wood/agri biochars report lower water absorption, chloride diffusion, and carbonation depths when BC is <5%. The added carbon also can slow ionic diffusion. However, high BC levels can create microcracks or increase porosity, so durability could degrade if replacement is too high (>10%). At lower BC contents, the

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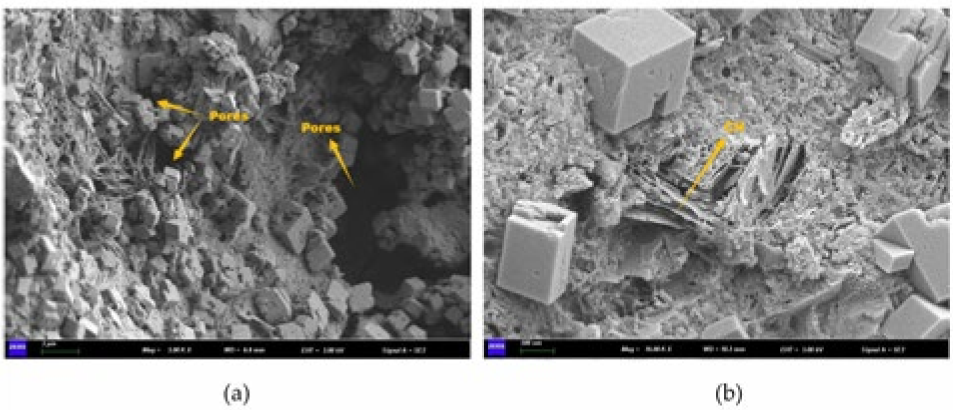
matrix exhibits a dense, pore-refined structure dominated by well-formed ettringite and C-S-H, suggesting enhanced nucleation via internal curing (Sikora et al., 2022). At higher BC dosages, morphology deteriorates into a porous, loosely bonded matrix with diminished AFt/C-S-H and a dominance of portlandite, indicating hydration inhibition due to water overabsorption and increased interfacial voids. Biochar's porous particles act as micro-fillers, filling voids and reducing overall porosity, with the ITZ benefiting from improved bonding and reduced microcracking. Table 5 show the durability properties of Palm Kernel shell biochar concrete.

Table 5: Durability properties of Palm Kernel shell biochar concrete

Study	**Biochar Type**	**Dosage**	**Durability Finding**	**Microstructure (SEM/MIP/XRD)**
Gupta et al. (2021)	Wood biochar	1 – 2 %	Improved resistance to permeability, shrinkage, sulfate attack, and chloride-induced corrosion at 1–2%	Denser pore structure; reduced capillary porosity vs. control
Shao et al. (2023)	Agricultural BC (varied fineness)	3%	Improved carbonation resistance and chloride ion penetration resistance at 3%; worsens at 10%	SEM at 3%: uniform ITZ, crack-free, fine hydration products on BC
Zhou et al. (2024)	Silica-rich biochar	2.70%	Enhanced C-S-H formation; BC acts as nucleation site	SEM: C-S-H crystals decorate BC pore surfaces; densified ITZ
Sustainable multifunctional BC review (2025)	Multiple (meta-review)	≤5 %	5% BC reduces water absorption up to 17%; pre-soaked BC reduces water penetration depth by 52–60%	MIP: decreased capillary porosity and more fine pores at low BC
Sirico et al. (2025)	Palm shell BC	1%	1% BC: minimal porosity; good hydration products	SEM: abundant C-S-H and well-formed ettringite; 24% BC shows unfilled pores

Microstructural Characterization: Scanning electron microscopy (SEM) in Figure 5 reveals that palm kernel shell biochar (PKSB) particles, typically ranging from 10 to 100 µm in size with irregular and porous morphology, are well-embedded within the hardened cement paste matrix (Zhou et al., 2023). At optimal low replacement levels (1–5 %), the interfacial transition zone (ITZ) appears dense, uniform, and largely crack-free, with fine hydration products (primarily C–S–H) nucleating and depositing on and within the biochar surfaces. Detailed SEM images of palm shell biochar in UHPC at 1% and higher dosages, showing dense hydration products and ITZ at low replacement.



(a) Control (b) 1% biochar

Figure 5: SEM images of palm shell biochar in concrete (Wu et al., 2025)

Optimization Techniques: Fundamentals of Response Surface Methodology: Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques widely employed for developing, improving, and optimizing processes governed by multiple interacting variables (Barton, 2013).

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Originally formalized by Box and Wilson (1951), RSM integrates the principles of designed experimentation with polynomial regression modeling to systematically map the functional relationship between a set of controllable input factors and one or more measured responses. The methodology is particularly well-suited to engineering and materials science applications, where process behavior is often nonlinear and factor interactions are non-negligible.

The core premise of RSM is the sequential approximation of the true response surface using low-order polynomial models — most commonly of quadratic form — fitted to data obtained from a structured experimental design. Once an adequate model is established, analytical tools including Analysis of Variance (ANOVA), desirability functions, and graphical response surface plots are applied to identify the combination of factor settings that optimizes the response of interest. A principal advantage of RSM over conventional one-factor-at-a-time (OFAT) experimentation is its capacity to detect and quantify interaction effects and curvature within the response surface while requiring substantially fewer experimental runs, thereby reducing both cost and time without sacrificing statistical rigor (Gunst et al., 1996; Lucas, 2010).

The validity and efficiency of an RSM study depend critically on the choice of experimental design, which must support the estimation of all linear, interaction, and quadratic model terms. Three designs are most prevalent in the literature:

Central Composite Design (CCD). The CCD augments a standard two-level factorial (2^k) or fractional factorial design with axial (star) points located at a distance α from the design center, and with replicated center points. This structure permits the simultaneous estimation of first-order, two-factor interaction, and pure quadratic effects, making the CCD the most versatile and widely adopted design in RSM applications (Lenth, 2020). The rotatable CCD, in which α = (2^k)^(1/4), ensures uniform prediction variance throughout the design space. CCD has been extensively applied in studies involving cementitious composites and biochar production, as discussed in Section 4.

Box–Behnken Design (BBD). The BBD is a spherical, three-level design that positions experimental points at the midpoints of the edges of a hypercube and at the center, deliberately excluding the corner points of the factorial space (Shao et al., 2024). For three to four factors, the BBD requires fewer experimental runs than a comparable CCD while maintaining adequate estimability of the quadratic model. Its exclusion of extreme factor combinations (i.e., corner points) renders it particularly appropriate when simultaneous application of all factors at their extreme levels is impractical or undesirable from a process-safety or material-stability perspective (Oyebanji et al., 2023).

Doehlert Design. The Doehlert uniform shell design distributes experimental points at equal distances on a circle (two factors), sphere (three factors), or higher-dimensional analogues, providing uniform coverage of the design space. Although less frequently employed in cement and biochar literature, the Doehlert design offers flexibility in the number of levels assigned to different factors and allows sequential augmentation of the design with minimal additional runs (Bezerra et al., 2008).

The selection among these designs is governed by the number of independent variables, the desired model resolution, practical constraints on experimental runs, and the distribution of prediction variance. For instance, Zhou et al. (2023) employed a BBD with two factors — biochar content and particle size — to model the compressive strength of biochar-modified mortar, while Onokwai et al. (2023) applied a CCD to five pyrolysis variables to maximize palm kernel shell biochar (PKSB) yield.

Following experimentation, the fitted RSM model is subjected to rigorous statistical diagnostics to confirm its adequacy before it is used for optimization. The principal metrics are as follows:

Coefficient of Determination (R^2). R^2 quantifies the proportion of total response variation explained by the regression model, ranging from 0 to 1. A value of $R^2 \geq 0.90$ is generally considered indicative of a well-fitted model in materials engineering contexts, and most validated RSM models reported in the cement and biochar literature meet or exceed this threshold (Boumaaza et al., 2023).

Adjusted R^2 (R^2_adj). The adjusted R^2 corrects for the number of model terms relative to the number of observations, penalizing the inclusion of non-contributory terms. A substantial discrepancy between R^2 and R^2_adj (conventionally defined as a difference exceeding 0.20) signals potential overfitting and warrants model reduction (Ullah et al., 2026).

Predicted R^2 (R^2_pred). The predicted R^2, typically estimated via leave-one-out cross-validation, reflects the model's capacity to predict responses at new, unobserved factor combinations. Alignment between R^2_pred and R^2_adj, without a difference exceeding 0.20, is required to confirm genuine predictive capability rather than mere interpolative fit (Boumaaza et al., 2023).

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p-Values and Term Significance. ANOVA partitions the total model sum of squares into contributions from individual terms. A p-value below 0.05 (at the 95% confidence level) denotes statistical significance for a given term or the overall model. Terms failing to reach significance are typically removed through backward elimination to yield a reduced, parsimonious model. Onokwai et al. (2023), for example, identified pyrolysis temperature as the most influential factor, with a model term p-value < 0.0001 (Onokwai et al., 2023).
Lack-of-Fit Test. The lack-of-fit F-test evaluates whether the residual variation is attributable solely to pure experimental error or also to systematic model inadequacy. A non-significant lack-of-fit ($p > 0.05$) is required, indicating that the chosen polynomial model captures the true response surface without systematic deviation. Sait et al. (2025) reported a non-significant lack-of-fit for their quadratic RSM model of PKSB yield, thereby confirming its statistical adequacy (Basma Yahya Alashwal et al., 2021).
Adequate Precision. This metric expresses the ratio of the range of predicted values across the design space to the average prediction error (noise). A value exceeding 4.0 is considered acceptable, signifying that the model can be used to navigate the design space with sufficient reliability (Zahraee et al., 2018).
Beyond these primary statistics, comprehensive model validation also encompasses examination of residual normality (via normal probability plots), absence of systematic trends in residual-versus-run plots, and independence of residuals, collectively ensuring that the fundamental assumptions of ordinary least squares regression are satisfied.
Graphical Interpretation and Optimization: Once a validated RSM model is established, contour plots and three-dimensional response surface plots serve as principal tools for visualizing the functional relationship between the input factors and the response. These graphical representations reveal the topology of the response surface, including ridges, saddle points, and optima, and facilitate the intuitive identification of factor settings that yield desirable response values. In cementitious composite research, for example, contour plots of compressive strength as a function of supplementary cementitious material content and water-to-binder ratio effectively delineate regions of optimal mix design.

Multi-response optimization is typically accomplished through the desirability function approach (Derringer & Suich, 1980), in which individual response desirabilities — each scaled between 0 and 1 — are combined into a composite desirability index. Maximizing this index with respect to the factor space yields the globally optimum conditions across all responses simultaneously. As a representative example, Zhou et al. (2023) applied this approach to identify an optimal biochar content of 2.69% at a median particle diameter of 51.1 µm, predicting a compressive strength approximately 10% above the control; this prediction was subsequently validated through confirmatory experimentation.

Essentially, RSM provides a statistically robust and experimentally efficient framework for the multi-variable optimization of PKSB production and application. Its capacity to model factor interactions and nonlinear response behavior, combined with the interpretive power of response surface visualization, makes it particularly well-suited to the complex process-property relationships inherent in biochar-modified cementitious systems. The following section synthesizes the existing RSM literature directly relevant to PKSB and presents a comparative tabulation of study designs, optimized conditions, and key outcomes.

Despite the growing body of research on PKSB as a supplementary cementitious material and soil amendment, the application of RSM to the systematic optimization of PKSB production and utilization remains comparatively limited.

Onokwai et al. (2023) conducted one of the most comprehensive RSM investigations of PKSB production to date, employing a CCD to evaluate the simultaneous effects of five pyrolysis parameters — temperature, residence time, heating rate, nitrogen flow rate, and feedstock particle size — on biochar yield. The resulting quadratic model demonstrated excellent predictive accuracy ($R^2 = 0.9887$), with pyrolysis temperature identified as the dominant factor ($p < 0.0001$). Optimal conditions were determined as 320°C, 6.5 min residence time, and associated gas flow and particle size settings, yielding a maximum PKSB yield of 41.1%.

Aman et al. (2023) applied a CCD with three pyrolysis variables — temperature, heating rate, and residence time — to jointly optimize multiple PKSB compositional properties, including yield, carbon content, oxygen content, and inorganic constituents (potassium and silicon). The desirability function approach yielded optimal conditions of 409°C, 15°C/min, and 120 min, producing a char with 38.2% yield and 73.4% fixed carbon content, demonstrating that moderate pyrolysis temperatures favor the simultaneous maximization of both yield and carbon enrichment.

Sait et al. (2025) employed a BBD to investigate the effects of pyrolysis temperature, nitrogen flow rate, and residence time on PKSB yield. The quadratic model exhibited strong statistical performance ($R^2 \approx$

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0.989, non-significant lack-of-fit), and optimal conditions were identified as approximately 800°C, 150 mL/min nitrogen flow, and 107.6 min, yielding 37.87% PKSB. Notably, this study incorporated an Artificial Neural Network (ANN) comparison, concluding that RSM provided superior predictive accuracy for this dataset, reinforcing RSM as the preferred optimization framework under conditions of moderate experimental complexity.

Zhou et al. (2023) shifted the focus from production to application, employing a BBD with two factors — biochar mass fraction and median particle diameter (D_{50}) — to optimize the 28-day compressive strength of biochar-modified cement mortar. Response surface analysis revealed a clear optimum at a biochar content of 2.69% and D_{50} of 51.1 µm, corresponding to a predicted compressive strength approximately 10% above the unmodified control, subsequently confirmed by experimental validation.

Beyond these PKSB-specific investigations, RSM has been applied to cement systems incorporating other biochars — including sugarcane bagasse and rice husk — providing methodological precedents transferable to PKSB-modified cementitious composites. However, the comparatively sparse PKSB-specific RSM literature underscores a significant research gap, particularly with respect to the joint optimization of pyrolysis conditions and resulting biochar properties as predictors of cementitious performance.

Across the reviewed studies, common pyrolysis factors include temperature and residence time (for production optimization) and biochar content and particle size (for mix design optimization). The convergence of optimized outcomes across independent studies — moderate pyrolysis temperatures in the range of 320–500°C for yield-carbon balance, and biochar replacement levels of 2–5% for compressive strength — provides a consistent empirical foundation upon which further RSM-guided PKSB optimization can be constructed. These findings directly inform the experimental design framework adopted in the present study, as detailed in the subsequent section. Table 6 consolidates the peer-reviewed RSM studies most directly relevant to PKSB, encompassing both pyrolysis process optimization and biochar-modified mix design, and provides a structured comparison of experimental designs, process variables, optimized responses, and model performance.

Table 6: Summary of RSM studies involving PKS biochar

Author (Year)	Material	Variables (Factors)	Design	Responses	Optimum Conditions	Main Findings
Onokwai et al. (2023)	PKS	Pyrolysis temperature (T), residence time (t), heating rate (HR), N_2 flow rate, feedstock particle size	CCD (5 factors)	Biochar yield (%)	T = 320°C, t = 6.5 min (with specified HR, N_2 flow, and particle size)	Maximum PKSB yield of 41.1%; R^2 = 0.9887; pyrolysis temperature was the dominant factor ($p < 0.0001$); significant interactions among all variables
Aman et al. (2023)	PKS	Pyrolysis temperature (T), heating rate (HR), residence time (t)	CCD (3 factors)	Biochar yield (%); Carbon content (%); Oxygen content (%); K and Si concentrations	T = 409°C, HR = 15°C/min, t = 120 min	Optimal yield of 38.2% with 73.4% fixed carbon; moderate temperature maximized yield–quality balance; multi-response optimization using desirability function
Sait et al. (2025)	PKS	Pyrolysis temperature (T), N_2 flow rate, residence time (t)	BBD (3 factors)	Biochar yield (%)	T ≈ 800°C, N_2 flow = 150 mL/min, t = 107.6 min	Maximum yield of 37.87%; R^2 ≈ 0.989 with non-significant lack-of-fit; RSM outperformed ANN in predictive accuracy

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Zhou et al. (2023)	PKS Biochar in mortar	Biochar mass fraction (%), median particle diameter (D_{50}, µm)	BBD (2 factors)	28-day compressive strength (MPa)	BC = 2.69 wt.%, D_{50} = 51.1 µm	~10% increase in 28-day compressive strength vs. control; particle fineness critical; response surface showed clear optimum; experimental validation confirmed predictions

The differing optimum conditions reported in Table 6 largely reflect differences in optimization objective (yield vs. carbon content vs. strength), the variables and ranges included in each design, and the specific design type (CCD, BBD, Doehlert) and reactor used — not necessarily contradictory material behavior. Since each model is valid only within its own tested design space and none has been cross-validated against an independent PKSB source, the generalizability of any single reported optimum beyond its original study remains unverified.

4.4 Environmental and Economic Assessment

Carbon Footprint (LCA): Using PKSB as cement replacement or additive can reduce the embodied CO_2 of concrete. LCA analyses (e.g. Aman 2025 thesis) show that even 4% cement replacement with PKSB can cut total concrete emissions by 20–40%. Specifically, Aman et al. (2025) found that in mortar, 4% PKSB (409°C char) reduced cradle-to-gate impact by ~17.2%, and in concrete by ~38.1%, relative to pure OPC concrete. These savings arise from (a) displacing clinker (each 1% cement replacement ~0.8% CO_2 reduction), and (b) sequestering carbon in the biochar (their best case captured ~14.4 kg CO_2 per kg PKSB). When fed into landfills or used as boiler fuel, PKS would emit its carbon, so using it as biochar avoids this.

Energy Use: Pyrolysis itself consumes energy. LCA must account for pyrolysis fuel (often natural gas or electricity) and biochar yield. Optimizing RSM conditions thus matters: e.g. lower T (400–500°C) saves energy but yields less char, whereas high T (800°C) gives more fixed C but higher energy per kg. A balanced optimum must consider net CO_2. Aman's LCA suggested that moderate conditions (500°C) gave the best emission savings in practice. In future, coupling pyrolysis with waste heat could improve economics.

Economic Costs: Quantitative cost studies on PKSB cement are sparse. Raw PKS is low-value or even a disposal burden, so feedstock cost is minimal (often negative). The main cost is processing: pyrolysis capital and operation. In tropical regions, small pyrolysis units (tons/day) could be integrated at mills. Cement is expensive ($100–150/t), so even 1–5% replacement saves material cost (though grinding biochar to cement fineness adds cost). Biochar markets in agriculture exist (soil amendment), which could improve project feasibility by selling co-products. Overall, life-cycle payback depends on local energy cost and carbon pricing.

Environmental and economic literature is limited by inconsistent LCA system boundaries (cradle-to-gate vs. cradle-to-grave) and functional units, which make reported emissions savings hard to compare across studies. Economic data are especially sparse, relying on assumed rather than measured pyrolysis costs with little sensitivity analysis. No study integrates techno-economic and life-cycle assessment with mechanical/durability optimization, so a strength- or durability-optimal mix may not be optimal environmentally or economically — a gap future work should address through standardized boundaries and multi-objective assessment.

4.5 Challenges, Research Gaps and Future Directions

Despite its promise, PKSB as an additive faces several challenges and gaps:

•Limited Durability Data: Long-term performance (50+ years) under aggressive environments (sulfate, chloride, freeze-thaw) is poorly known. Most studies focus on early-age strength; more testing of durability indicators is needed.

•Standardization of PKSB: Variability in PKS feedstock (age, species, processing) can affect biochar properties. Standard testing protocols (particle size, carbon content, mineralogy) are needed for quality control.

•Workability and Mix Design: As noted, PKSB reduces slump. Research should quantify admixture needs (superplasticizers or viscosity modifiers) specifically for PKSB mixes, to allow higher replacement levels without compromise.

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•Scale-up and Cost: Most studies are lab-scale. Piloting pyrolysis in mills, ensuring consistent char quality, and integrating with cement plants are necessary steps. Comprehensive cost analysis (energy, labor, transport) is currently lacking.
•Environmental Impacts Beyond CO_2: Potential emissions from pyrolysis (e.g. tars, VOCs) and toxicity (if any) require assessment. Also, the end-of-life (e.g. demolition) fate of carbon in biochar-enriched concrete needs study.

Future Research: Key directions include: (1) Machine learning and RSM hybrid: Recent work (Sait et al.) shows combining RSM with ANN yields even better predictions. Future studies can use ML to fine-tune multi-objective optimization (e.g. strength and CO_2). (2) Combinatorial SCMs: Investigate PKSB blended with other SCMs (fly ash, calcined clay) for synergy. (3) Mechanistic studies: In-depth characterization of hydration chemistry with PKSB (using nanoanalysis, tomography) would clarify its micro-filler vs. nucleation roles. (4) Field tests: Trials in real concrete elements (not just mortar) to assess construction performance. (5) Policy and incentives: As governments push low-carbon materials, life-cycle labeling of PKSB concrete could drive adoption.

5.0 Conclusions

Palm kernel shell biochar is an abundant, low-cost material with significant potential as a carbonaceous filler and multifunctional cementitious additive, rather than a true pozzolanic SCM. Review of the literature shows that properly produced PKSB (slow pyrolysis at ~400–800°C) is predominantly carbon (~70–80%) with negligible reactive silica (<0.5% SiO_2), and functions in cement primarily through pore filling, ITZ refinement, and hydration nucleation rather than pozzolanic reaction. At replacement levels reported across the literature as optimal (typically 1–5%, though the specific optimum varies with curing regime, w/b ratio, and particle fineness), PKSB has been shown to enhance compressive strength by up to ~40% at early ages and to improve select durability indicators, while contributing to carbon sequestration. RSM has proven valuable for optimizing both PKSB production and cement mix design; representative studies report optimal pyrolysis conditions near 409°C and 120 min residence time, and optimal mix parameters near 2.7% biochar content at ~51 μm particle size using CCD/BBD designs — though these optima are design-space-specific and have not been cross-validated across independent PKSB sources. Environmental assessments report CO_2 reductions in the range of ~20–40% relative to control mixes, though system boundaries and functional units vary enough across studies to limit direct comparison. Principal challenges remain in feedstock and process standardization, long-term (multi-year) durability validation, integrated techno-economic assessment, and scale-up beyond laboratory conditions; addressing these gaps through standardized testing protocols and cross-study validation is a prerequisite for reliably integrating PKSB into circular-economy concrete production. This review provides a consolidated knowledge base, comparative tables, and a clarified functional classification to guide researchers developing optimized PKSB-modified concrete.

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