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SUSTAINABLE STABILIZATION OF LATERITIC SOILS USING COCONUT FIBER ASH, RICE HUSK ASH, AND PALM KERNEL SHELL ASH: A COMPREHENSIVE REVIEW

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Abstract: The sustainable stabilization of lateritic soils in tropical regions is an urgent necessity, particularly in rapidly urbanizing areas like Lagos State, Nigeria, where subgrade failures and poor road performance are prevalent due to highly plastic and moisture–sensitive soils. This literature review evaluates the potential of three agro–waste ashes [Coconut Fibre Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA)] as eco–friendly soil stabilizers. These waste materials are available in large quantity in Nigeria and cause environmental pollution. The review synthesizes findings from over 30 empirical studies, detailing the geotechnical and chemical properties of these ashes and their effects on soil performance indicators such as California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Plasticity Index (PI), Maximum Dry Density (MDD), and Optimum Moisture Content (OMC). Results indicate that CFA enhances soil strength and workability, with studies reporting up to 45% increase in CBR and significant PI reduction at 10–15% content. RHA demonstrates superior pozzolanic activity, improving UCS by 50–60% and CBR by up to 100% in some lateritic soils. PKSA, although less studied, has shown promising results, with UCS improvements of up to 55% and swelling potential reduction when used at 6–10%. Chemical analysis reveals that all three ashes meet ASTM C618 Class F pozzolan criteria, with silica modulus values ranging from 2.0 to 40. Geotechnically, these ashes reduce PI, enhance strength parameters, and exhibit favorable compaction behavior, especially when ground to finer particles. Despite these promising findings, the review identifies research gaps including limited studies on ternary blends, lack of durability data, and inadequate microstructural characterization using SEM and XRD techniques. The study concludes that ternary blends of CFA, RHA, and PKSA will offer synergistic benefits for lateritic soil stabilization and are well–suited for sustainable road construction in Nigeria.
Keywords: Agro–waste, Coconut Fibre Ash (CFA), Lateritic soils, Palm Kernel Shell Ash (PKSA), Rice Husk Ash (RHA), Stabilization, Pozzolanic materials

1. INTRODUCTION

Lateritic soils are widely encountered in the southwestern region of Nigeria, particularly in Lagos State and its surrounding areas. These soils are typically rich in iron and aluminum oxides and exhibit high plasticity, variable strength, and significant sensitivity to moisture content (Adedokun et al., 2023) Consequently, when used as subgrade or base materials in road construction, untreated lateritic soils often exhibit poor bearing capacity and are prone to excessive deformation under traffic loading—especially during the long rainy seasons characteristics of the region. This presents a critical challenge for the sustainable development of road infrastructure in Lagos, which is a rapidly expanding megacity with increasing demands on its transportation network (Abiola et al., 2022). According to (Aiyewalehinmi and Adeyemi, 2014), Lateritic soils are the softer, less cemented soils formed below or adjacent to laterite crusts. These soils have higher clay content and show greater variability in plasticity, gradation, and strength. Their engineering behavior often requires stabilization for use in road construction or embankments.

Studies show that lateritic soils have diverse particle size distribution and flexibility, unlike the more uniform structure of hardened laterites. Compaction and moisture content significantly influence lateritic soils, while laterites are less affected due to their cemented nature (David, 2009). Specific gravity is another distinguishing property. Lateritic soils typically show an increase in specific gravity with advanced weathering as heavier minerals concentrate (Hill et al., 2000). Laterites, having already undergone extensive weathering, usually maintain consistently higher specific gravity and strength (Amu and Adetuberu, 2010). While laterites generally exhibit high strength and low compressibility, lateritic soils display a wider range of engineering properties like moisture content, wet and dry densities, and void ratio. Unfortunately, detailed studies on these bulk properties remain limited (Oyetayo et al., 2012).

Traditional soil stabilization techniques, particularly the use of cement and lime, have been widely adopted to enhance the engineering properties of problematic soils. While these methods are effective, they come with significant limitations, including high material costs, carbon emissions from production processes, and limited accessibility in rural and semi-urban areas. As sustainability becomes a core consideration in civil engineering and infrastructure development, (Bell, 2007), there is a growing interest in identifying alternative stabilization methods that are both environmentally friendly and economically viable (Awoyera and Akinmusuru, 2016).

In this context, the utilization of agricultural waste ashes as soil stabilizers has emerged as a promising solution. Nigeria, being an agrarian economy, generates substantial quantities of biomass waste. In Lagos State alone, large volumes of coconut fibers, rice husks, and palm kernel shells are produced daily through agricultural processing, food markets, and street vending (FAO, 2022). These residues are typically discarded, burned, or left to decompose, contributing to environmental pollution and public health risks. However, when appropriately incinerated under controlled conditions, these agro-wastes yield ashes that are rich in reactive silica and alumina key components responsible for pozzolanic activity (Adedokun et al., 2025).

Coconut Fibre Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA) have individually exhibited considerable potential to enhance the geotechnical performance of soils through pozzolanic reactions, which result in the development of cementitious compounds when combined with water and calcium-rich additives. While previous studies have investigated the effects of these ashes in isolation or in binary combinations, there is limited research on their combined (ternary) effects on lateritic soil stabilization, particularly within the local context of Lagos and its unique climatic and geotechnical conditions (Yusuf et al., 2019), (Ettu et al., 2018), (Adebisi et al., 2012).

Coconut Fibre Ash

Coconut Fibre Ash (CFA) is generated from the controlled combustion of coconut coir, which forms the fibrous layer covering coconut shells. In Nigeria, especially in coastal regions like Lagos, Badagry, and Lekki, significant quantities of coconuts are processed, producing around 300,000 metric tonnes of husks annually (Assam and Agunwamba, 2020). Improper disposal or open burning of these husks often leads to environmental pollution. CFA stands out for its rich reactive silica content, giving it pozzolanic potential. Research has shown CFA can enhance the load-bearing performance of lateritic soils and reduce plasticity (Olutaiwo et al., 2020). Observed notable increases in the California Bearing Ratio (CBR) when CFA was used for soil stabilization. Beyond road applications, CFA has also been explored in lightweight concrete and eco-friendly construction materials (Azeez et al., 2022).

Rice Husk Ash

Rice Husk Ash (RHA) results from burning rice husks, a by-product of the rice milling process. With states like Kebbi, Benue, and Ebonyi leading rice production, Nigeria produces approximately 200,000–300,000 tonnes of rice husks each year (Azeez et al., 2022). While uncontrolled burning is common, controlled combustion produces ash with high reactive silica content, typically exceeding 80%. The pozzolanic characteristics of RHA make it valuable in improving soil strength, reducing swelling, and enhancing durability (Gidigasu et al., 2021). For instance, (Eze and Okafor, 2022) found that adding RHA improved the strength of expansive soils, while (Iwuji et al., 2021) highlighted its effectiveness in boosting subgrade bearing capacity. Additionally, RHA will helps to reduce the overall use of cement in construction, supporting sustainability.

Palm Kernel Shell Ash

Palm Kernel Shell Ash (PKSA) is derived from burning palm kernel shells, a major waste product from Nigeria's palm oil industry, which generates over 1.4 million tonnes annually (Akshatha and Namratha, 2020). Much of this material remains underutilized or is burned inefficiently, contributing to environmental issues. Due to its alumina and silica content, PKSA offers promising pozzolanic properties. (Adekunle and Oyediran, 2021) reported that integrating PKSA into clayey soils enhanced their unconfined compressive strength by over 25%. Its applications extend beyond soil stabilization to include sustainable concrete production and paving blocks (Abiola et al., 2022).

2. SOIL STABILIZATION USING AGRO-WASTES

Soil stabilization aims to enhance the engineering properties of soils, particularly those characterized by low strength and high moisture sensitivity. While traditional stabilizers such as cement and lime have long been employed, there is increasing interest in more sustainable alternatives like agro-waste ashes. Materials including rice husk ash, palm kernel shell ash, coconut fiber ash, sugarcane bagasse ash, and corn cob ash provide dual benefits: they not only improve soil strength but also help mitigate environmental waste. Owing to their high silica and alumina content, these ashes exhibit pozzolanic properties that contribute to increase in unconfined compressive strength (UCS) and California Bearing Ratio (CBR), while simultaneously reducing swelling and plasticity (Amu et al., 2011), (Bello et al., 2018), (Rahman et al., 2014). Through pozzolanic reactions with water and calcium, these by-products form cementitious compounds such as calcium silicate hydrate (C-S-H), which enhance soil strength and reduce permeability. The utilization of agro-waste ashes thus promotes resource recycling and aligns with sustainable construction practices.

Coconut Fibre Ash (CFA)

CFA has been investigated for its cementitious potential in soil stabilization. Studies (Table 1) have shown that CFA, when properly incinerated, is rich in amorphous silica and carbon, which contributes to improved soil strength, especially when used in combination with other pozzolanic materials (Umar and Bala, 2020), (Oladele et al., 2016). Studies (Table 1) show that CFA typically contains a significant percentage of Silicon dioxide (SiO_2): 40-65%, Calcium oxide (CaO): 5-15%, Aluminum oxide (Al_2O_3): 3-15%, Iron oxide (Fe_2O_3): > 5%. These oxide contents make CFA comparable to other pozzolanic materials like fly ash and rice husk ash (RHA). According to (Awoyera and Akinmusuru, 2016), the reactivity of CFA is enhanced when burned at temperatures between 600-800°C, making it suitable for partial replacement of cement or as a soil stabilizer.
Recent research emphasizes the pozzolanic properties of Coconut Fiber Ash (CFA) in stabilizing lateritic soils (Olutaiwo et al., 2020). It observed that adding CFA improved the California Bearing Ratio (CBR) and reduced plasticity index, enhancing soil strength (Tables 2 and 3). The study by (Umar and Bala, 2020) also found similar benefits, showing that CFA increases unconfined compressive strength (UCS) and supports better compaction. Additionally, (Muhammad, 2024) investigated CFA as a mineral filler in asphalt mixtures, highlighting its contribution to improved durability and reduced environmental impact. These studies confirm CFA's potential as a cost-effective and eco-friendly soil stabilizer, particularly in tropical regions with abundant coconut waste.

Table 1: Chemical Properties of CFA, RHA, and PKSA

Property / Oxide Composition	Coconut Fibre Ash (CFA)	Rice Husk Ash (RHA)	Palm Kernel Shell Ash (PKSA)	References
SiO_2	40–65%	80–90% (mostly amorphous)	55–65%	(Azeez et al., 2022), (Eze and Okafor, 2022), (Iwuji et al., 2021)
Al_2O_3	3–15%	1–2%	10–18%	(Yusuf et al., 2019), (Olutaiwo et al., 2020)
Fe_2O_3	6–10%	1–2%	8–12%	(Assam and Agunwamba, 2020), (Eze and Okafor, 2022)
CaO	5–15%	0.5–2%	5–10%	(Ettu et al., 2018), (Azeez et al., 2022)
MgO	1–3%	1–2%	1–3%	(Oyetayo et al., 2012)
$K_2O + Na_2O$ (Alkalis)	2–6%	1–3%	2–4%	(Yusuf et al., 2019)
LOI (Loss on ignition)	6–12%	4–8%	5–10%	(Amu and Adetuberu, 2010), (Akshatha and Namratha, 2020)
Pozzolanic classification	Class F (ASTM C618)	High reactivity; rich in amorphous silica	Class F	(Assam and Agunwamba, 2020) (Akshatha and Namratha, 2020)

Table 2: Geotechnical Properties of CFA, RHA, and PKSA

Property	Coconut Fiber Ash (CFA)	Rice Husk Ash (RHA)	Palm Kernel Shell Ash (PKSA)	References
Specific gravity	1.8–2.3	1.9–2.3	1.8–2.4	(Ettu et al., 2018), (Olutaiwo et al., 2020), (Azeez et al., 2022).
Bulk density	500–650 kg/m^3	500–600 kg/m^3	550–700 kg/m^3	(Amu and Adetuberu, 2010), (Yusuf et al., 2019).
Main oxide composition	SiO_2 50–65%; Al_2O_3 10–15%; Fe_2O_3 6–10%	SiO_2 80–90%	SiO_2 55–65%; Al_2O_3 10–18%; Fe_2O_3 8–12%	(Azeez et al., 2022), (Eze and Okafor, 2022), (Akshatha and Namratha, 2020).
Fineness (passing 75µm sieve)	≥70% (after grinding)	≥90%	≥80%	(Yusuf et al., 2019), (Eze and Okafor, 2022).
Pozzolanic activity	Moderate	High (due to amorphous silica)	Moderate	(Assam and Agunwamba, 2020), (Akshatha and Namratha, 2020).
Effect on plasticity index (PI)	Lowers PI slightly	Significantly lowers PI	Lowers PI moderately	(Aiyewalehinmi and Adeyemi, 2014), (Azeez et al., 2022).
Effect on compaction (OMC, MDD)	Increases OMC; slightly reduces MDD	Same trend; higher OMC due to high surface area	Increases OMC; lowers MDD	(Oyetayo et al., 2012), (Ettu et al., 2018).
CBR improvement	Moderate increase; better in blends	Significant increase	Moderate increase	(Aiyewalehinmi and Adeyemi, 2014), (Amu and Adetuberu, 2010).
Unconfined compressive strength (UCS) effect	UCS improves; best with lime or cement	Strong UCS gain	UCS increases moderately	(Yusuf et al., 2019), (Assam and Agunwamba, 2020),

Table 3: Coconut Fibre Ash (CFA) Past Studies, Results and Limitations

Reference	Soil Type	% CFA added	Key results	Limitations
Adebisi et al., 2012 (Busari et al., 2018)	Lateritic soil	2–10% CHA At 4% (similar to CFA)	Decreased in PI from 23% to 18%; Increased in plastic limit; CBR improved from 19% to 36%; MDD peaked at 4% CHA	Focused only on lateritic soil; no durability (wet–dry) test; small sample size; no microstructural analysis
Akshatha (Widianti et al., 2024)	Expansive clay	2–12% CFA	UCS increased from 50–60% at 6% CFA; reduced swelling	No chemical activation studied
Onyelowe (Widianti et al., 2023)	Black cotton soil	At 10% CFA	UCS increased significantly; swelling decreased; soaked CBR increased from 8% to 25%	No SEM/XRD to show reaction products
Prabakar (Adebisi et al., 2019)	Clayey soil	CFA + lime	UCS doubled vs. lime–only; PI reduced	Only studied lime–CFA blend; unclear effect of CFA alone
Abhishek (Shagaya et al., 2024)	Black cotton soil with alkali–activated CHA	15%	UCS increased; denser pore structure (SEM); FTIR confirmed C–S–H	Needs chemical activator higher cost and complexity; focused on expansive clay only
Widianti (Neville, 2021)	Expansive clay	0.75% coir fiber + 6–8% CWA (coir wood ash)	Optimum 6–8% with fiber gave highest gains; swelling eliminated, Unsoaked CBR 534%, Soaked CBR 503%, UCS 349%, Tensile 105%, Swell 0%	Lab study; ≤28 d curing; no durability checks.
Widianti (Alhassan, 2008)	Soft clay	0.75% coir fiber 8% CHA–wood ash	Shear strength 210% vs fiber–only (21 days), Peak deviator stress, cohesion, φ, shear strength at 8%.	Compared to fiber–only; no durability test
Abhishek (Shagaya et al., 2024)	Black cotton soil (BCS)	CHA–AAB 9% (binder)	UCS 466% (182 ⟶ 1030 kPa, 28 d) 68% at 24 h (182 ⟶ 305 kPa) Alkali–activated CHA improved early and 28–d UCS; pore refinement	Needs alkaline activators; durability beyond 28 d not studied
Yusuf (Amagu et al., 2022)	Lateritic subgrade (A–2–6)	CHA up to 20%	Improved CBR and strength up to 8%. Performance peaked around 8% then declined.	Exact % gains not reported

Coconut fibre ash, generated from the combustion of coconut husks, has been explored as a pozzolanic material in both concrete and soil stabilization applications. It contains silica, carbon, and alumina in various proportions depending on combustion conditions. CFA has been shown to enhance strength, reduce plasticity, and increase resistance to environmental degradation when added to lateritic soils. (Olutaiwo et al., 2020) evaluated the effect of CFA on lateritic soil and observed significant improvement in CBR and UCS, reported notable increases in CBR and UCS values of CFA-treated soils, making it a suitable candidate for subgrade improvement in coastal and tropical areas such as Lagos State. (Umar and Bala, 2020) reported that adding CFA up to 15% improved CBR by up to 45%. (Muhammad, 2024) investigated CFA as a mineral filler in asphalt mixtures, showing improved stiffness and durability. (Widianti et al., 2024) reviewed eco-friendly soil stabilization materials, including CFA, highlighting its environmental benefits and engineering potential.

Research by (Olutaiwo et al., 2020) demonstrated that adding CFA (5-15%) to lateritic soils improved: California Bearing Ratio (CBR) by up to 45%, Unconfined Compressive Strength (UCS), Plasticity Index (PI) reduction, Maximum Dry Density (MDD) increase with decreasing Optimum Moisture Content (OMC). This is due to pozzolanic reactions forming calcium-silicate-hydrate (C-S-H) gel, which binds soil particles together. Adebisi (Adebisi et al., 2012) investigated the effect of adding 2-10% Coconut Husk Ash (CHA, chemically similar to CFA) to lateritic soils. Results demonstrated increase in plastic limit and reduction in plasticity index, indicating improved workability. Maximum dry density (MDD) increased slightly at optimum CHA content (around 4%), while optimum moisture content (OMC) initially reduced then increased. Soaked California Bearing Ratio (CBR) improved significantly, reaching 36% with 10% CHA, compared to 19% for untreated soil. These findings highlight CFA's potential as an effective partial stabilizer, especially in road subgrades where moderate improvement in bearing capacity is beneficial. (Abhishek et al., 2025) applied alkali-activated CHA to expansive black cotton soils, and reported that UCS increased significantly, with microstructural analysis showing denser matrices and lower mean pore sizes. Pozzolanic reaction products (C-S-H and C-A-H gels) contributed to the strength gain. Reduction in swelling potential and plasticity index. However, this method required chemical activation (using sodium hydroxide/silicate) to realize its full pozzolanic potential.

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Rice Husk Ash (RHA)

RHA is one of the most researched agro-waste ashes in soil stabilization. It has been reported to significantly improve the California Bearing Ratio (CBR), unconfined compressive strength (UCS), and reduce plasticity of various tropical soils (Tables 2 and 4). RHA's high silica content makes it highly reactive, and it has been successfully blended with lime or cement to enhance stabilization outcomes (Rahman et al., 2014), (Neville, 2021). Approximately 100 million tonnes of agro-waste materials, such as rice husk, are produced. Twenty percent of the composition of rice husks is inorganic, while eighty percent is organic. Rice husks are incinerated to generate rice husk ash. RHA is a very pozzolanic material. The RHA's elevated specific surface area and amorphous silica confer its notable pozzolanic activity (Neville, 2021). RHA is generated through the combustion or incineration of waste rice husk from paddy fields. RHA can serve as a pozzolan in lime and cement mixtures due to its elevated silica content. Consequently, the utilization of RHA alongside lime and cement is crucial.

Alhassan (Alhassan, 2008)examined the potential of RHA for soil stabilisation. It was incorporated at 2 to 12% by weight of the dry soil for stabilization. The study employed a lateritic soil sample from the Maikunkele district of Minna, classified as A-7-6 according to the AASHTO classification system. The performance of the soil-RHA at the BSL compaction energy level was evaluated regarding compaction properties, CBR testing, and UCS tests. The study's results indicated a general reduction in MDD and a rise in OMC corresponding to RHA concentration. The CBR and UCS exhibited minimal enhancement with the RHA content, as per the study. The performance of the treated soil for geotechnical structures beyond road bases was not evaluated; however, peak UCS values were observed between 6 and 8% RHA, suggesting limited potential for utilizing 6 to 8% RHA to enhance the strength of A-7-6 lateritic soil. RHA is recognized for its high silica content (Table 1) and reactivity, which make it suitable for soil stabilization. Recent studies (Tables 2 and 4), including (Eze and Okafor, 2022), demonstrate that RHA significantly improves the strength and durability of expansive soils while lowering plasticity. (Iwuji et al., 2021) also reported that incorporating RHA into lateritic soils enhanced subgrade bearing capacity, making it suitable for road construction. (Shagaya et al., 2024) further explored the combined use of RHA and marble dust, showing that this blend reduced moisture susceptibility and improved soil stiffness. Overall, these findings highlight RHA's dual role in improving engineering performance and promoting sustainable waste management.

Gidigasu (Amagu et al., 2022) used waste crushed rock stabilized lateritic soil and spent carbide blends. (Alhassan and Osinubi, 2022) reviewed challenges and new techniques in lateritic soil stabilization, specifically mentiOng RHA's role. (Busari et al., 2018) used aluminum dross with lateritic soil, comparable to how RHA functions as a pozzolan. RHA's potential as a stabilizer continues to emerge from controlled burning processes that preserve its high silica content. (Faluyi et al., 2025) reported that combining 6% lime with 4% RHA in Southwest Nigerian lateritic soils—using eighteen different samples—increased compaction density, UCS, CBR, cohesion, and internal friction angle while reducing Plasticity Index (PI) , Studies like (Igibah et al., 2022) demonstrated that using 6% cement with 6% RHA significantly reduced PI and improved triaxial performance , while (Idris et al., 2022) found that 10% RHA with 5% cement yielded optimal compaction and CBR for subgrade use. (Oguche et al., 2024) used 6% RHA on lateritic clay, raising UCS from ~50 KPa to ~65 KPa and (Ogunribido et al., 2024) reported similar CBR improvements at 4% RHA. These studies show that RHA with or without cement or lime is an effective, eco-friendly stabilizer in tropical soils.

Rice husk ash has been extensively studied (Table 1) due to its high content of amorphous silica. When incinerated at controlled temperatures, RHA develops high pozzolanic reactivity, which is effective in stabilizing clayey and lateritic soils. Studies (Table 4) have demonstrated that RHA improves strength and compaction properties, reduces permeability, and enhances long-term durability (Tables 2 and 4). RHA is particularly useful in tropical areas where rice farming is prevalent (Rahman et al., 2014), (Neville, 2021).

Table 4: Rice Husk Ash (RHA) Past Studies, Results and Limitations

Reference	Soil type	% RHA added	Key results	Limitations
Basha et al., 2005.	Expansive clay	20%(with or without lime)	UCS and soaked CBR increased; PI decreased; optimum at 12% RHA	Only one agro waste; no durability test
Osinubi et al., 2022	Lateritic soil	12% At 8%	CBR increased from 18% to 36% at 8% RHA; PI decreased	Only one agro waste: burning temperature effect not studied

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Jain et al., 2012	Black cotton soil	5–20% At 10%	UCS increased from 35–50%; swelling decreased; best at 10% RHA	Limited to black cotton soils; no microstructural analysis
Alhassan M, 2008.	Clayey soil	0–12% At 8%	Optimum UCS and CBR at 8% RHA; PI decreased	Small sample sizes; no durability evaluation
Basha et al., 2005	Residual soil	RHA + lime	UCS roughly doubled vs. lime alone; improved moisture resistance	Needed chemical activation; RHA effect alone not isolated
Aiyewalehinmi A and Adeyemi A, 2014.	Lateritic soil	0–12% 12%	CBR increased up to 50%; PI decreased; MDD increased slightly	No durability test conducted
Hossain et al., 2016.	Soft clay	5–15% At 15%	Significant UCS gain; reduced compressibility and swelling	Only soft clays; no field–scale validation
Sabat P, 2012.	Expansive soil	RHA + lime	UCS increased 80%; PI decreased; pozzolanic reaction	Needed lime activation; RHA alone not tested
Rahman et al., 2018.	Peat soil	10–30% At 30%	UCS increased; compressibility decreased	Focused on organic soils; higher dosages; risk of excess filler
Ahmed et al., 2021.	Expansive clay	4–12% At 12%	UCS increased 60%; PI decreased; SEM confirmed denser matrix & C–S–H	Lab–scale only; no field validation; single soil type
Chen et at., 2022.	Silty clay	5–15% At 15%	CBR increased from 10% to 28%; UCS increased; improved moisture resistance	Short curing period; no XRD analysis
Kumar et at., 2023.	Lateritic soil	0–12% At 12%	PI decreased by 30%; UCS increased 50%; FTIR identified pozzolanic products	Only few laboratory tests; no durability test
Okafor, F. C., and Adeyemi, D. U. 2024.	Black cotton soil	2–10% At 10%	UCS increased; swelling potential decreased by 40%; better compaction	SEM and XRD were not conducted.
Nahar et al., 2021.	A–2–4 soil (silty sand)	0–15%	Burnt RHA improved bearing resistance and stiffness; peak at 5% with CBR of 39.5%.	Durability and microstructural test were conducted.
Wibowo et al., 2023.	fine soils	0–12% RHA with 0–9% cement	Bearing Capacity Ratio 200–450% (Wates), 10–110%; Model embankments: RHA+cement boosted bearing capacity; stronger effect on OH soil.	Model scale; blended binder (RHA+cement).
Bhunia et al., 2023.	Black cotton soil (expansive)	>20% RHA	Large CBR gains at >20% (CBR > +600% RHA) swelling and PI decreased. Swelling reduced	No durability test conducted.
Falade et al., 2025.	Clayey lateritic subgrade	RHA + cement blends (varied %)	CBR, UCT, MDD all increased, RHA+cement improved strength/stiffness; suitable subgrade stabilizer.	Blended binder focus, few % ratio was considered.
Hidalgo et at., 2020.	Low–plasticity clay subgrade	RHA + SCBA (varied %)	CBR increased, PI decreased (values depend on mix); Pozzolanic ash blends improved CBR and reduced PI	Blended with SCBA; isolated RHA effect not singular.
Ewa et at., 2018.	Road subgrade	Varied %	Performance sensitive to RHA source, Showed RHA chemical variability affects outcomes.	Focus on variability; not a single optimized %.

Palm Kernel Shell Ash (PKSA)

PKSA though less studied than RHA, is gaining traction in geotechnical applications. PKSA is typically rich in potassium, silica, and alumina (Table 1). Research has demonstrated its ability to reduce plasticity, increase soil compaction characteristics, and improve strength when used as a partial replacement for cement in soil stabilization (Ewa et al., 2018), (Adebisi et al., 2019). Its availability in oil-producing regions makes it an attractive low-cost alternative. In regions of palm oil production, especially in southern Nigeria, palm kernel shell is an abundant and readily available waste material. The amounts of ash and Sulphur in palm kernel shells are exceedingly low. The residue from combusting palm kernel shells at a controlled temperature range of 600 to 1000°C is referred to as palm kernel shell ash (PKSA). The utilization of PKSA is minimal and impractical, with most being discarded as waste in landfills, resulting in environmental concerns (Bell, 2007).

Onyelowe (Onyelowe, 2016) evaluated the influence of palm kernel shell ash (PKSA) and coconut shell ash (CSA) on the axial load and compaction characteristics of lateritic soil stabilized with pozzolan. He utilized lateritic soil from Oboro, Delta State, for his research, incorporating coconut shell husk ash and palm kernel shell husk ash in incremental concentrations of 2, 4, 6, 8, and 10%, respectively, relative to the dry weight of the soil sample. The addition of varying amounts of CSHA and PKSA resulted in an increase in the optimum moisture content and a decrease in the maximum dry density. The UCS data indicate enhancement in treated soil with 10% CSHA and

PKSA; however, triaxial test results showed a decrease in both unit weight and dry unit weight at varying percentages of CSHA and PKSA.

Palm Kernel Shell Ash has gained attention for its alumina and silica content, which contribute to its pozzolanic reactivity. (Adebisi et al., 2019) demonstrated that PKSA increases the UCS of clayey soils by over 25%, while (Adekunle and Oyediran, 2021) confirmed PKSA's potential as an alternative to cement in lateritic soil stabilization. (Abiola et al., 2022) reviewed PKSA's broader applications, noting its use in sustainable concrete and paving blocks. (Ezreig, 2022) also emphasized PKSA's environmental benefits in reducing carbon emissions and utilizing local agro-waste. Collectively, these studies reinforce PKSA's viability in enhancing soil properties and contributing to greener construction practices. PKSA continues to show value beyond its traditional use in cement composites. Recent works from (Subair et al., 2024) combined 4% PKSA with 2% RHA on lateritic soil for pavement use, raising CBR from 27% to 41%, improving maximum dry density (MDD), and adjusting optimum moisture content (OMC) Another study using PKSA and eggshell ash (ESA) showed significant improvements in compaction and soaked/unsoaked CBR, with PKSA/ESA blends rendering lateritic soil suitable for sub-base applications. Recent studies (Table 5) PKSA has been tested as partial replacement for cement and shown to improve compaction, reduce plasticity, and increase durability.

PKSA is an abundant by-product of palm oil production in West Africa. Rich in silica, alumina, and potassium oxide, it exhibits considerable pozzolanic activity. Studies (Ewa et al., 2018), (Adebisi et al., 2019) show that PKSA, when used in partial replacement with cement or alone in soil, improves strength and reduces swell potential. Its availability and low cost make it a viable alternative stabilizer for road construction in regions with high palm oil production like Nigeria.

Table 5: Palm Kernel Shell Ash (PKSA) Past Studies, Results and Limitations

Study	Soil type	% PKSA added	Key results	Limitations
Amu et al., 2011.	Lateritic soil	2–10% 4% achieved highest	At 4% UCS increased by 40%; soaked CBR increased from 25% to 48%; PI decreased	Single agro waste only; No durability test
Oluremi, J. A., and Bamisaye, R. A. (2019).	Expansive clay	2–12% 8% achieved heighest	Swelling potential decrease; PI decrease; UCS increase at 8% PKSA	Single agro waste only: No SEM/XRD;
Oluwatudimu et al., 2020.	Black cotton soil	2–12% 6% achieved highest	At 6% CBR increased from 12% to 27%; UCS increased; PI decreased	Single agro waste only; no durability test
Assam, J., and Agunwamba, C. (2020).	Clayey soil	2–7% 4.5% achieved highest	At 4.5% UCS increased from 287 kN/m^2 to 433 kN/m^2 (50%) CBR (unsoaked) 5.3%–8.2% (55%) CBR (Soaked) 3.9%–5.3% (36%); PI decreased by 25%; improved compaction	Single agro waste only
Adeboje, T. (2016).	Lateritic soil	5–12.5% 12.5% achieved highest	CBR increases by 161% significantly; swelling decreased	No microstructural study; short curing; Single agro waste only
Akinwumi, A. (2018).	Lateritic soil	2–8% (with lime)	CBR: soil met base course requirements, peak at 8%	PKSA effect not isolated (tested with lime)
Amagu et al 2022.	Compacted shale (A–7–5) for landfill liner	0–12% PKSA (with PPKS)	LL & PL decreased; OMC increased; MDD decreased; permeability decreased; suitable for liners, at 12% recorded peak	PKSA effect mixed with PPKS; durability study
Subair et al., 2024.	Lateritic soil for pavement	0, 3, 6, 9%	UCS from 394 kPa (0%) to1022 kPa (9%); OMC increased; MDD: decreased, peaked at 9%	Binary blend, not PKSA alone; limited curing
Oni et al., 2025.	Lateritic soil	4% PKSA + 2% RHA	CBR increased to 41%; improved base/sub–base strength 4% PKSA +2% RHA, peaked at 4% PKSA (with 2% RHA)	Some mixes <30% CBR; requires activator & curing
Oluremi et al 2019.	Laterite soil	3, 6, 9%	CBR increased up to 77% vs natural; geopolymerized PKSA 50% higher than plain 9% (geopolymerized)	No durability test
Aliyu, M. (2021).	Expansive clay	4–12%	UCS increased 55%; swelling decreased; SEM showed denser matrix	Single agro waste only; no durability test
Okeke, N. (2023).	Black cotton soil	3–12%	UCS increased; PI decreased by ~30%; FTIR identified C–S–H	Single agro waste only
Muhammad, I. (2024).	Lateritic soil	0–10%	UCS increased ~45%; swelling potential decreased by ~35%	Single agro waste only; no durability study

Gaps Identified from the Literature Review

The gaps identified in the review of the existing literatures on the stabilization of soil with coconut fibre ash are itemized below.

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1. Limited research specifically on Coconut Fiber Ash (CFA). Most studies focus on Coconut Husk Ash (CHA) or raw fibers; CFA (from burning coir fibers) is less documented, especially its pozzolanic properties and chemical composition.
2. Lack of standardized mix designs and activation methods, Long-term durability data missing, Microstructural characterization is limited. Only some studies employed SEM, XRD, FTIR to explain mechanisms; many remain empirical without linking mineralogical changes to strength gain.
3. Environmental and economic analyses. Little data on cost-benefit, embodied energy, CO_2 savings, or environmental impact compared to cement or lime.
4. Existing studies clearly demonstrate Ashes' promise in improving soil strength, reducing plasticity, and enhancing bearing capacity. However, the research is still limited by mostly small-scale, short-term testing, Lacking systematic mix optimization, durability studies, ternary combinations of the ashes.

These gaps justify further research, such as studying the ternary combination of the agro-waste ashes such as CFA, RHA and PKSA. Evaluating durability, environmental benefits, and cost. In addition, the impacts of the composite mixture of the alkali activators and coconut fibre ash on the geotechnical properties of residual soils have not been adequately investigated.

3. CONCLUSION & RECOMMENDATIONS

This review has established that the stabilization of lateritic soils with agro-waste ashes specifically coconut fibre ash (CFA), rice husk ash (RHA), and palm kernel shell ash (PKSA) presents a sustainable, cost-effective, and technically viable alternative to traditional stabilizers such as cement and lime. Existing studies consistently demonstrate that these materials enhance the geotechnical performance of lateritic soils by improving strength, durability, workability, and compaction characteristics, while simultaneously reducing the environmental burden associated with agricultural waste disposal.

The pozzolanic reactivity of these ashes facilitates the formation of secondary cementitious compounds, leading to improved interparticle bonding and enhanced resistance to moisture-induced deterioration. Furthermore, literature indicates that ternary blends of different agro-waste ashes can generate synergistic effects, resulting in superior stabilization outcomes compared to single-ash applications.

Despite these promising findings, the variability in ash chemical composition, differences in processing methods, and lack of standardized evaluation procedures remain critical challenges. Addressing these limitations through targeted research particularly under tropical climatic conditions prevalent in regions such as Lagos State—will be essential for optimizing mix design and ensuring consistent field performance.

Following the review of existing studies on lateritic soil stabilization with agro-waste materials, the following directions are suggested for future work:

- Blend Optimization: Investigate a range of mix proportions of Coconut Fibre Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA) to establish an optimum ternary combination that ensures adequate strength, durability, and environmental benefits for pavement subgrade and base layers.
- Performance under Tropical Climate: Undertake extended monitoring of stabilized soils under Lagos' climatic conditions, with emphasis on durability aspects such as wet-dry cycles, erosion resistance, and leaching, which remain underexplored in current research.
- Complete Geotechnical Evaluation: Many previous works were limited to basic tests. Future studies should comprehensively evaluate the engineering properties of lateritic soils treated with agro- and industrial-waste ashes, and directly compare these results with conventional cement stabilization.
- Durability Testing: Beyond consistency and strength indices, additional durability parameters such as permeability, swelling behavior, shrinkage, and strength loss should be assessed and benchmarked against cement-stabilized soils.
- Microstructural Insights: Future studies should employ advanced mineralogical and microstructural analyses (e.g., XRD, SEM, EDS) to clarify the pozzolanic reaction mechanisms of each ash type, as well as their interactive behavior when blended.
- Processing Standards: Establish standardized local processing procedures—including burning conditions, grinding, and sieving—to enhance ash reactivity and ensure consistent field performance

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— Field Demonstration Projects: Implement pilot road construction schemes within Lagos State using ternary ash blends, coupled with systematic performance monitoring under actual traffic and environmental conditions.

In summary, agro-waste-based soil stabilization aligns with the principles of sustainable construction by promoting resource efficiency, reducing greenhouse gas emissions, and lowering infrastructure costs. Its adoption holds considerable potential for advancing resilient and environmentally responsible geotechnical engineering practices in developing economies.

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