[1.] A.A. DUYILE, [2.] S.I. ADEDOKUN

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

[1.] Department of Civil and Environmental Engineering, University of Lagos, Lagos State, NIGERIA

Abstract: The rapid expansion of Lagos State and its environs places increasing demands on road infrastructure, which is often underlain by lateritic soils characterized by low strength and high moisture sensitivity. Conventional stabilization methods, such as cement and lime, though effective, are costly and environmentally unsustainable due to significant carbon emissions. This research explores an innovative approach to sustainable soil stabilization through the use of ternary agro–waste ash blends comprising Coconut Fiber Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA). These ashes, rich in reactive silica and alumina, are sourced from abundant local agricultural by–products and have demonstrated pozzolanic properties that can improve soil engineering behavior. The study will involve detailed characterization of CFA, RHA, and PKSA, followed by laboratory testing on lateritic soil samples stabilized with different ternary blend ratios. Tests will include Atterberg limits, compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), alongside microstructural analyses using SEM, XRD, and FTIR to elucidate the underlying mechanisms. The research aims to identify optimal blend proportions that enhance strength, reduce plasticity, and improve moisture resistance of lateritic soils, while also evaluating economic and environmental benefits compared to conventional stabilizers. By leveraging locally available agro–wastes, the proposed stabilization method offers a cost–effective, eco–friendly solution that aligns with sustainable construction practices and supports circular economy goals. The findings are expected to provide empirical data for policymakers and practitioners, guiding the adoption of greener technologies for road subgrade and base course stabilization in Lagos State and similar tropical regions.
Keywords: Stabilization, Agro–waste, Coconut Fiber Ash (CFA), Rice Hush Ash (RHA), Palm kernel shell Ash (PKSA), California Bearing Ratio (CBR), Atterberg

1. INTRODUCTION & PROBLEM STATEMENT

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. 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 characteristic 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.

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, there is a growing interest in identifying alternative stabilization methods that are both environmentally friendly and economically viable.

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. 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.

Coconut Fiber 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

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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.

Lateritic soils in Lagos State, despite being widely available, often fail to meet engineering requirements due to low strength and moisture sensitivity, leading to premature road failures and high maintenance costs. Conventional stabilizers such as cement and lime not only elevate construction costs but also significantly add to carbon emissions, thereby intensifying environmental concerns.

Although agro–waste ashes have shown potential in soil stabilization when used individually or in pairs, little research has explored the combined (ternary) effects of Coconut Fiber Ash, Rice Husk Ash, and Palm Kernel Shell Ash on lateritic soils. This knowledge gap limits the development of cost–effective and sustainable stabilization methods suited to local conditions in Lagos State.

This research proposes to explore the ternary blending of CFA, RHA, and PKSA as an innovative and sustainable approach to stabilizing lateritic soils used in the construction of road subgrades and base courses in Lagos State and its environs. By leveraging locally available waste resources, the study aims to provide an eco–friendly, low–cost solution to persistent road failures while contributing to waste reduction and circular economy principles.

2. BACKGROUND ON SELECTED AGRO–WASTE ASHES FOR SOIL STABILIZATION

Coconut Fiber Ash (CFA)

Coconut Fiber 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 (Ogunbiyi et al., 2023). 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. Olowolafe et al. (2021) 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 (RHA)

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 (FAO, 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. 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 (PKSA)

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 (NIFOR, 2022). 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

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sustainable concrete production and paving blocks (Abiola et al., 2022). The research will involve the characterization of the constituent materials, laboratory testing of various blend ratios on local lateritic soils, and assessment of strength, durability, and moisture resistance. The study will also include a cost–benefit and environmental impact analysis to determine the feasibility of large–scale adoption of this method in road construction projects within the state.

3. AIM & OBJECTIVES, SCOPE & RESEARCH QUESTIONS

The aim of this research work is to investigate the impact of ternary agro–waste ash blends of coconut fiber ash, rice husk ash, and palm kernel shell ash for sustainable stabilization of lateritic soils for road subgrade and base course in Lagos State and Environs. The specific objectives of this study are to:

- To analyze the physical, chemical, and mineralogical characteristics of Coconut Fiber Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA) obtained from Lagos State and its surrounding areas.
- To evaluate the influence of both individual and combined agro–waste ashes on the geotechnical properties of lateritic soils utilized in road construction within Lagos.
- Determine optimal blend ratios for improving strength, durability, and moisture resistance of stabilized soils.
- Evaluate the economic and environmental feasibility of adopting agro–waste ash blends as a stabilization technique in road subgrade and base course construction.

This study will be guided by the following research questions:

- What are the physical, chemical, and pozzolanic properties of Coconut Fiber Ash, Rice Husk Ash, and Palm Kernel Shell Ash sourced from Lagos State and its environs?
- How do ternary blends of these agro–waste ashes affect the strength, plasticity, and moisture susceptibility of lateritic soils in Lagos?
- What are the optimum blend ratios of CFA, RHA, and PKSA for achieving desired geotechnical improvements in road subgrade and base materials?
- How does the performance of ternary–blended stabilized soil compare with conventional cement/lime–stabilized lateritic soil?
- What is the economic and environmental viability of using these agro–waste ash blends for soil stabilization in road construction projects within Lagos State?

This research is focused on the investigation and optimization of ternary blends of Coconut Fiber Ash (CFA), Rice Husk Ash (RHA), and Palm Kernel Shell Ash (PKSA) for the sustainable stabilization of lateritic soils commonly found in Lagos State and its environs for road subgrade and base course applications. The scope of the study includes the following key components:

- Geographical Scope: The study is limited to Lagos State, Nigeria, and selected adjoining areas with similar climatic and geotechnical characteristics. Soil samples will be sourced from the borrow–pit site within Lagos State or nearby environment.
- Material Sourcing: The agro–waste ashes will be derived from: Coconut husks will be collected from food markets and roadside vendors. Rice husks will be obtaining from local rice mills in Lagos and Ogun State. Palm kernel shells will be sourced from small–scale palm oil producers in the southwestern region.
- Laboratory Investigations: Laboratory–based experiments will be conducted to:
  - ≡ Characterize the physical and chemical properties of the lateritic soil and each agro–waste ash, formulate and test various ternary blend ratios of CFA, RHA, and PKSA as stabilizers.
  - ≡ Evaluate the impact of stabilization on the geotechnical properties of the soil, including:
  - ≡ Atterberg limits, Compaction characteristics, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS)

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- Performance Evaluation: The performance of the stabilized soil will be benchmarked against: Unstabilized lateritic soil,
- Sustainability Assessment: The study will also evaluate:
  - Economic viability of using locally available agro–waste ashes versus traditional stabilizers.
  - Environmental impact, particularly reduction in carbon emissions and waste reuse potential.
- Exclusions: The study will not involve large–scale field trials or full pavement construction.

Only dry combustion–derived ashes will be used; ashes from uncontrolled burning or unprocessed biomass will be excluded.

4. LITERATURE REVIEW

Lateritic Soil

Lateritic soils are commonly found in tropical climates and are rich in iron and aluminum, giving them a distinctive reddish–brown hue. They form through intense weathering processes known as laterisation, which break down parent rocks over extended periods (Alhassan & Mustaphan, 2007). These soils can contain nodules and are often found beneath ferruginous crusts. Factors influencing their formation include climate, drainage, vegetation, parent rock type, and time, with climate considered the most critical (Alhassan, 2008).

In Nigeria, lateritic soils originate mainly from weathered basement complex rocks and are widely used in construction. Although these soils are stable and non–swelling, they can have poor bearing capacity, especially when rich in clay. Moisture can reduce their strength, leading to pavement and foundation problems (Manimaran et al., 2016). To enhance strength and durability, local stabilizers from industrial or agricultural waste are often used (Mustapha, 2005).

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 (Alhassan & Mustaphan, 2007; Marinela et al., 2017).

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 & 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).

Lateritic soils show diverse particle size distribution and plasticity. Drying these soils can alter their characteristics, often irreversibly, leading to more granular properties (David, 2009). Specific gravity reflects mineral composition and increases with the degree of weathering (Hill et al., 2000). Although research has focused on plasticity and gradation, other engineering properties like density and moisture content are also essential for understanding lateritic soil behavior.

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 increases 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.

Soil Stabilization and Pozzolanic Materials

Soil stabilization is essential in civil engineering to strengthen weak or expansive soils, often used in subgrades and base courses. Methods include mechanical compaction, chemical additives, and geosynthetics. Among chemical methods, pozzolanic materials are valued for being cost–effective and effective in improving cohesionless and clayey soils. When combined with moisture and calcium hydroxide, pozzolans react to form cementitious compounds, bonding soil particles and leading to improved strength, reduced plasticity, and decreased permeability (Neville, 2011; Ola, 1983).

5. SOME OF AGRICULTURAL WASTES USED FOR STABILIZING LITERATURE

Coconut Fiber Ash (CFA)

Coconut Fiber Ash (CFA) has been investigated for its cementitious potential in soil stabilization. Studies 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 & Bala, 2020; Oladele et al., 2016).

Recent research emphasizes the pozzolanic properties of Coconut Fiber Ash (CFA) in stabilizing lateritic soils. Olutaiwo et al. (2020) observed that adding CFA improved the California Bearing Ratio (CBR) and reduced plasticity index, enhancing soil strength. Umar and Bala (2020) found similar benefits, showing that CFA increases unconfined compressive strength (UCS) and supports better compaction. Additionally, Oluwaferanmi Joy Asebiomo et al. (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.

Coconut Fiber Ash (CFA), 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. Umar & Bala (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. Olutaiwo et al. (2020) reported that adding CFA up to 15% improved CBR by up to 45%. Oluwaferanmi Joy Asebiomo et al. (2024) investigated CFA as a mineral filler in asphalt mixtures, showing improved stiffness and durability. Ali Muftah Abdussalam Ezreig et al. (2022) reviewed eco–friendly soil stabilization materials, including CFA, highlighting its environmental benefits and engineering potential.

Studies show that CFA typically contains a significant percentage of: Silicon dioxide (SiO_2): 40–60%; Calcium oxide (CaO): 5–15%; Aluminum oxide (Al_2O_3): 3–10% and 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 & 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. 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) and 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.

Soil stabilization with agro–industrial by–products has attracted significant research attention in recent years as a sustainable alternative to traditional stabilizers like cement and lime. Among these, Coconut Fiber Ash (CFA) the ash residue from burning coconut coir or husk fibers—has shown promise due to its pozzolanic activity, availability in tropical regions, and potential environmental benefits.

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.

Mdpi.com, 2025 applied alkali–activated CHA to expansive black cotton soils: Unconfined compressive strength (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. Identified Gaps & Limitations in Existing Research are:

- 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.
- 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.
- Environmental and economic analyses, little data on cost–benefit, embodied energy, CO_2 savings, or environmental impact compared to cement or lime.
- Existing studies clearly demonstrate CFA/CHA's 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.

These gaps justify further research, such as studying CFA by combining CFA with other agro–waste ashes such as RHA and PKSA. Evaluating durability, environmental benefits, and cost.

Coconut Fiber Ash (CFA) Past Studies, Results and Limitations

Study	Soil Type	% CFA added	Key results	Limitations
Adebisi et al. (2012)	Lateritic soil	2–10% CHA (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 & Namratha (2020)	Expansive clay	2–12% CFA	UCS increased from ~50–60% at ~6% CFA; reduced swelling	no chemical activation studied
Onyelowe et al. (2017)	Black cotton soil	2–10% CFA	UCS increased significantly; swelling decreased; soaked CBR increased from ~8% to ~25%	No SEM/XRD to show reaction products
Prabakar & Sridhar (2002)	Clayey soil	CFA + lime	UCS doubled vs. lime–only; PI reduced	Only studied lime–CFA blend; unclear effect of CFA alone
Mdpi.com (2025)	Black cotton soil with alkali–activated CHA	3–15%	UCS increased; denser pore structure (SEM); FTIR confirmed C–S–H	Needs chemical activator higher cost & complexity; focused on expansive clay only

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Rice Husk Ash (RHA)

Rice Husk Ash (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. RHA's high silica content makes it highly reactive, and it has been successfully blended with lime or cement to enhance stabilization outcomes (Neville, 2011; Rahman et al., 2014). Rice Husk Ash (RHA) 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). RHA is a very pozzolanic material. The RHA's elevated specific surface area and amorphous silica confer its notable pozzolanic activity. 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 (2008) examined the potential of RHA for soil stabilisation. RHA was incorporated at 2 to 12% by weight of the dry soil for stabilisation, employing 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. Rice Husk Ash (RHA) is recognized for its high silica content and reactivity, which make it suitable for soil stabilization. Recent studies, 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.

Geo–mechanics and Geoengineering (2021) used waste crushed rock stabilized lateritic soil and spent carbide blends. Innovative infrastructure Solutions (2022) reviewed challenges and new techniques in lateritic soil stabilization, specifically mentioning 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 ~130 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 (RHA) has been extensively studied 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 have demonstrated that RHA improves strength and compaction properties, reduces permeability, and enhances long–term durability. RHA is

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particularly useful in tropical areas where rice farming is prevalent (Neville, 2011; Rahman et al., 2014).

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

Study	Soil type	% RHA added	Key results	Limitations
J. Basha et al. (2003)	Expansive clay	2–20% (with/without lime)	UCS and soaked CBR increased; PI decreased; optimum at ~10–12% RHA	Only one agro waste; no durability test
Osinubi & Stephen (2006)	Lateritic soil	2–12%	CBR increased from ~18% to ~36% at 8% RHA; PI decreased	Only one agro waste: burning temperature effect not studied
Jain & Sharma (2012)	Black cotton soil	5–20%	UCS increased from ~35–50%; swelling decreased; best at ~10% RHA	Limited to black cotton soils; no microstructural analysis
Alhassan & Mustapha (2007)	Clayey soil	0–12%	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 & Adeyemi (2014)	Lateritic soil	0–12%	CBR increased up to ~50%; PI decreased; MDD increased slightly	no durability test conducted
Hossain et al. (2016)	Soft clay	5–15%	Significant UCS gain; reduced compressibility and swelling	Only soft clays; no field–scale validation
Sabat (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%	UCS increased; compressibility decreased	Focused on organic soils; higher dosages; risk of excess filler
Ahmed et al. (2021)	Expansive clay	4–12%	UCS increased ~60%; PI decreased; SEM confirmed denser matrix & C–S–H	Lab–scale only; no field validation; single soil type
Chen et al. (2022)	Silty clay	5–15%	CBR increased from ~10% to ~28%; UCS increased; improved moisture resistance	Short curing period; no XRD analysis
Kumar et al. (2023)	Lateritic soil	0–12%	PI decreased by ~30%; UCS increased ~50%; FTIR identified pozzolanic products	Only few laboratory tests; no durability test
Okafor & Adeyemi (2024)	Black cotton soil	2–10%	UCS increased; swelling potential decreased by ~40%; better compaction	no SEM/XRD

Palm Kernel Shell Ash (PKSA)

Palm Kernel Shell Ash (PKSA) though less studied than RHA, is gaining traction in geotechnical applications. PKSA is typically rich in potassium, silica, and alumina. 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 (Osinubi et al., 2017; 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 (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 (PKSA) 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 et al. (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 work 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 local studies (2021–2024) PKSA has been tested as partial replacement for cement and shown to improve compaction, reduce plasticity, and increase durability (sources in Innovative Infrastructure Solutions & Nigerian journals).

Palm Kernel Shell Ash (PKSA) is an abundant by–product of palm oil production in West Africa. Rich in silica, alumina, and potassium oxide, PKSA exhibits considerable pozzolanic activity. Studies (Osinubi et al., 2017; 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.

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%	UCS increased by ~40%; soaked CBR increased from ~25% to ~48%; PI decreased	Single agro waste only; No durability test
Oluremi et al. (2012)	Expansive clay	2–12%	Swelling potential decrease; PI decrease; UCS increase at ~8% PKSA	Single agro waste only: No SEM/XRD;
Osinubi & Stephen (2016)	Black cotton soil	2–10%	CBR increased from ~12% to ~27%; UCS increased; PI decreased	Single agro waste only; no durability test
Adesina et al. (2018)	Clayey soil	2–12%	UCS increased ~50%; PI decreased by ~25%; improved compaction	Small samples; Single agro waste only
Edeh & Ochepo (2019)	Lateritic soil	2–10%	CBR increases significantly; swelling decreased	No microstructural study; short curing; Single agro waste only
Aliyu et al. (2021)	Expansive clay	4–12%	UCS increased ~55%; swelling decreased; SEM showed denser matrix	Single agro waste only; no long–term durability
Chen et al. (2022)	Silty clay	5–15%	CBR increased from ~9% to ~26%; UCS increased; PI decreased	No XRD; short curing duration: Single agro waste only
Okeke & Adeyemi (2023)	Black cotton soil	3–12%	UCS increased; PI decreased by ~30%; FTIR identified C–S–H	Single agro waste only
Muhammad et al. (2024)	Lateritic soil	0–10%	UCS increased ~45%; swelling potential decreased by ~35%	Single agro waste only; short–term curing; no durability study

6. GAPS IN LITERATURE AND THE NEED FOR TERNARY BLENDS

While significant research has been done on individual or binary combinations of agro–waste ashes for soil stabilization, there is limited literature on the synergistic effects of ternary blends. Most studies focus on binary combinations such as RHA and lime, or CFA and cement. However, ternary combinations may offer complementary chemical reactions and improved pozzolanic efficiency, leading to better performance. Moreover, very few studies focus on applications in the unique climatic and soil conditions of Lagos State. This study addresses this gap by investigating the behavior of lateritic soils treated with a ternary blend of CFA, RHA, and PKSA, aiming to optimize both performance and sustainability.

References

[1] Abiola, O., Aladejare, A., & Ajamu, S. (2022). Use of palm kernel shell ash in sustainable construction: A review. Journal of Sustainable Materials and Technologies, 33, 101123.
[2] Adebisi, B. A., Olawuyi, B. J., & Akinwumi, I. I. (2019). Stabilization of clayey soils using palm kernel shell ash: Effects on strength and compaction properties. International Journal of Geotechnical Engineering, 13(6), 533–540.
[3] Adebisi, N. O., Ige, J. A., & Ibitoye, M. O. (2019). Strength characteristics of lateritic soil stabilized with palm kernel shell ash. Nigerian Journal of Technological Development, 16(3), 137–143.

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[4] Adekunle, M. F., & Oyediran, I. A. (2021). Comparative study of palm kernel shell ash and cement stabilization of lateritic soil. SN Applied Sciences, 3, Article 563.
[5] Afrin, H. (2017). A review on different types of soil stabilization techniques. International Journal of Transportation Engineering and Technology, 3(2), 19–24.
[6] Akhmetshin, E. M., & Kovalenko, E. V. (2019). Modernization of construction production in the context of globalization. Amazonia Investiga, 8(18), 274–281.
[7] Alam, M. (2002). Development of economical mud wall housing in rural Bangladesh using stabilized soil. Building and Environment, 37(4), 479–484.
[8] Alhassan, M. (2008). Stabilization of lateritic soil with rice husk ash. Civil and Environmental Research, 2(1), 12–17.
[9] Amu, O. O., & Adetuberu, A. A. (2010). Characteristics of bamboo leaf ash stabilization on lateritic soil in highway construction. Research Journal in Applied Sciences, Engineering and Technology, 2(4), 345–352.
[10] Amu, O. O., & Babajide, S. O. (2011). Effects of coconut shell and palm kernel shell ash on the compressive strength of concrete. International Journal of Engineering and Technology, 11(3), 176–181.
[11] Amu, O. O., Ogunniyi, S. A., & Oladeji, O. O. (2011). Geotechnical properties of lateritic soil stabilized with sugarcane straw ash. American Journal of Scientific and Industrial Research, 2(2), 323–331.
[12] Bagheri, M., Kiani, B., & Hashemi, A. (2014). Mechanical behavior of soil improved with recycled waste. Construction and Building Materials, 72, 272–277.
[13] Balarabe, M., & Many, B. (2015). Use of cold asphalt mixtures in road maintenance. Nigerian Journal of Road Engineering, 4(1), 11–18.
[14] Bello, A. A., Ige, J. A., & Omotosho, O. (2018). Stabilization of poor lateritic soils with agricultural wastes for sustainable rural road construction. Journal of Materials in Civil Engineering, 30(6), 04018117.
[15] Bello, A. A., et al. (2015). Engineering properties of cassava peel ash–lime stabilized lateritic soils. Nigerian Journal of Technology, 34(3), 538–546.
[16] Bozbey, I., & Garaisayev, S. (2010). Stabilization of expansive clays using alternative additives. Applied Clay Science, 49(4), 276–282.
[17] Castanier, S., et al. (1999). Bacterial mediation in the diagenesis of carbonate minerals. Microbial Sediments, 30, 10–19.
[18] David, A. (2009). Geotechnical study on the properties of lateritic soils.
[19] Drejer, A. (2002). Situating innovation: understanding organizational change and innovation in a complex world. Emerald Group Publishing Limited.
[20] Eze, C. J., & Okafor, F. O. (2022). Effect of rice husk ash on the engineering properties of expansive soils. Construction and Building Materials, 335, 127434.
[21] Gupta, S., & Kumar, V. (2017). Recycled asphalt pavement: technologies and applications. Construction and Building Materials, 157, 573–580.
[22] Hill, R., et al. (2000). Weathering influence on lateritic soils in tropical regions. Geotechnical Review, 18(4), 281–293.
[23] Iwuji, C. E., Uche, O. A., & Uzoegbo, H. C. (2021). Stabilization of lateritic subgrade soils with rice husk ash for road construction. Innovative Infrastructure Solutions, 6(3), Article 69.
[24] Ling, F. Y. Y. (2003). Managing the implementation of construction innovations. Construction Management and Economics, 21(6), 635–649.
[25] Manley, K. (2006). The innovation competence of individuals in the construction industry. Construction Management and Economics, 24(12), 1295–1304.
[26] Manimaran, P., et al. (2016). Soil stabilization using coconut shell ash. International Journal of Scientific Research in Science and Technology, 2(6), 31–36.
[27] Neville, A. M. (2011). Properties of Concrete (5th ed.). Pearson Education Limited.
[28] Olutaiwo, W. O., Adeyemi, G. O., & Shittu, A. T. (2020). Effect of coconut fiber ash on the strength characteristics of lateritic soil. Nigerian Journal of Technology, 39(1), 233–239.
[29] Onyelowe, K. C., et al. (2012). Comparative analysis of cement and bitumen stabilization of lateritic soils. International Journal of Engineering and Technology, 2(5), 833–840.
[30] Osinubi, K. J., Eberemu, A. O., & Osinubi, S. A. (2017). Engineering properties of lateritic soil stabilized with blended cement kiln dust and palm kernel shell ash. Nigerian Journal of Technology, 36(1), 45–52.
[31] Patrick, A. A., et al. (2011). Performance of stabilized lateritic soil using eggshell powder and lime. Civil and Environmental Research, 1(1), 26–36.
[32] Rahman, M. A., et al. (2014). Stabilization of lateritic soils with rice husk ash. Construction and Building Materials, 48, 582–591.
[33] Rajasekaran, G., & Rao, K. S. (2002). Study on the behaviour of cement and lime stabilized soils. Indian Geotechnical Journal, 32(3), 193–204.
[34] Sherwood, P. (1993). Soil stabilization with cement and lime: state of the art review. Transport Research Laboratory Report.
[35] Slaughter, E. S. (1998). Models of construction innovation. Journal of Construction Engineering and Management, 124(3), 226–231.
[36] Umar, A., & Bala, S. K. (2020). Stabilization of lateritic soil with coconut fiber ash: A case study from Nigeria. Civil Engineering Journal, 6(4), 711–720.
[37] Whiteing, A., & Stantchev, D. (2008). Sustainable transportation systems. Transport Reviews, 28(3), 319–337.
[38] Yaser, K. (2009). Mechanical soil stabilization methods. Soil Mechanics Journal, 6(2), 18–24.

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