International Journal of Multidisciplinary Department
Published by: International Journal & Research Global Publisher
ISSN: 3108-2718

Research Article

EVALUATION OF PALM KERNEL SHELL ASH AND RICE HUSK ASH AS STABILIZING AGENTS FOR LATERITIC SOILS IN ROAD PAVEMENT APPLICATIONS

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Article History:
Received: 28 March 2026 | **Accepted:** 02 April 2026 | **Published:** 07 April 2026
DOI: https://doi.org/10.5281/zenodo.19451806

*** Related declarations are provided in the final section of this article.*

Abstract

This empirical investigation evaluates the geotechnical modifications induced by integrating rice husk ash alongside palm kernel shell ash into lateritic earth. Subsurface materials were excavated from a depth of one meter along Iraa Road in Offa, Kwara State, Nigeria, following the careful stripping of the organic top layer to ensure sample purity. A rigorous suite of laboratory assessments was deployed to determine how specific dosages of these agro-wastes alter the foundational California Bearing Ratio (CBR), Maximum Dry Density (MDD), and Optimum Moisture Content (OMC). In its pristine state, the sampled earth yielded a CBR of 27%, denoting a subgrade of merely passable quality. However, introducing a binder matrix composed of 2% rice husk ash and 4% palm kernel shell ash propelled the CBR up to 41%, translating to a formidable upgrade in structural load endurance. Concurrently, the moisture demand (OMC) shifted upwards from 12.60% to 16.10%, while the dry density (MDD) saw a marginal but vital enhancement from 1.67 kg/m³ to 1.72 kg/m³, a shift indicative of superior particle amalgamation and compaction mechanics. Notably, escalating the binder concentrations beyond this precise threshold triggered a deterioration in the geotechnical indices, proving that an optimal saturation point exists, beyond which additional ash impairs structural cohesion. Ultimately, these laboratory outcomes validate that a meticulously calibrated blend of these two ashes fundamentally upgrades the mechanical limits of lateritic soils. Utilizing these specific byproducts delivers an ecologically sound, financially viable methodology for reinforcing pavement subgrades while simultaneously mitigating massive agricultural waste burdens.

Keywords: Lateritic earthwork, Agro-waste stabilization, Subgrade fortification, Geotechnical engineering, Rice husk byproduct, Palm kernel residue, Eco-conscious construction materials.

1. Introduction

The relentless surge in both industrial and agricultural outputs globally has inadvertently spawned massive volumes of residual waste, creating profound ecological and fiscal dilemmas. Finding environmentally sound avenues to repurpose this refuse is an urgent global mandate, particularly regarding their integration into civil infrastructure. Within the realm of highway engineering, repurposing these byproducts as partial substitutes or primary binding agents for traditional construction supplies can drastically curb environmental degradation, slash financial expenditures, and preserve finite raw resources.

Lateritic earth is abundantly scattered throughout tropical zones, including the Nigerian landscape, serving as a primary resource for formulating sub-base and subgrade pavement layers. Despite their sheer abundance, such geological deposits frequently suffer from inferior mechanical traits, including erratic bearing capacities, elevated plasticity, and a severe vulnerability to moisture-driven morphological changes. As a direct consequence, these sub-optimal earth materials mandate robust chemical or mechanical enhancement prior to their deployment in heavy load-bearing pavement networks. Historically, civil engineers have leaned heavily on established binders like lime or Portland cement; however, these conventional agents carry exorbitant price tags and generate massive carbon footprints, prompting modern researchers to aggressively pursue greener alternatives.

Recent scholarly investigations emphasize the untapped capabilities of specific agro-industrial residues—namely palm kernel shell ash (PKSA) and rice husk ash (RHA)—to function as highly potent soil modifiers. These particular ashes exhibit rich pozzolanic characteristics, allowing them to chemically interact with natural soil minerals to synthesize cement-like compounds that fundamentally fortify structural longevity and mechanical strength. Specifically, RHA—harvested through the precise thermal reduction of raw rice husks—is exceptionally dense in reactive silicates, whereas PKSA contributes essential metallic oxides that facilitate superior particle fusion and mass densification when applied in conservative doses.

Fusing these two waste streams yields a remarkably progressive technique for ground modification, holding particular relevance for emerging economies where such residues are ubiquitous yet chronically underutilized. Deploying this dual-ash strategy does more than merely elevate the earth's load-bearing limits; it also pioneers a highly effective model for sustainable waste diversion. Consequently, amalgamating these particular ashes generates an ecologically responsible, budget-friendly mechanism for rehabilitating fragile foundations, especially within developing nations. Across Nigeria, both RHA and PKSA are generated in staggering quantities but are frequently discarded haphazardly, triggering secondary ecological crises. Harnessing them for geotechnical engineering thereby champions responsible refuse recycling while fundamentally enriching the mechanical profile of native lateritic soils.

This research holds profound relevance by championing the ecological repurposing of industrial and farming byproducts for earthworks, supplying a green substitute to carbon-heavy traditional binders. By dissecting the synergistic impact of combining PKSA with RHA, this study seeks to actively lower infrastructure expenditures, curtail ecological contamination, and vastly upgrade the load-bearing efficacy of the tropical lateritic deposits utilized in contemporary roadworks. The empirical insights generated here hold critical value for nations like Nigeria, leveraging indigenous waste surpluses to fuel resilient public infrastructure while solving critical waste disposal bottlenecks.

2. Methodology

Raw lateritic earth was harvested alongside Iraa Road in the Offa region of Kwara State, Nigeria. To ensure sample integrity, the topsoil was stripped away, allowing pure material extraction from a depth of roughly one meter. These geological specimens were rigorously sealed against moisture loss and relocated to a controlled laboratory environment for comprehensive evaluation. The required rice husk ash was synthesized from indigenous husks via meticulous calcination and atmospheric burning, whereas the palm kernel shell ash was generated by subjecting raw shells to heavily monitored thermal decomposition. Following combustion, both ash variants were passed through fine sieves and kept in strictly desiccated conditions until required for the stabilization trials.

The earth modification protocol required blending the host soil with a static 4% ratio of PKSA, alongside fluctuating concentrations of RHA—specifically 0%, 2%, and 4%—measured relative to the dry soil mass. A battery of foundational laboratory examinations was executed in strict adherence to authoritative guidelines (specifically AASHTO and BS 1377), encompassing Atterberg limits, sieve analysis, compaction behaviors, and California Bearing Ratio evaluations.

The raw rice husks utilized in this investigation were procured from an active milling facility situated in Offa, Kwara State. After a 24-hour sun-drying phase, the husks were incinerated openly before undergoing calcination within a muffle furnace operating at roughly 600 °C, a process ensuring the creation of an exceptionally fine, silica-dense powder. Similarly, the palm kernel components were sourced directly from regional suppliers. To prepare them, the raw shells were thoroughly laundered to extract any lingering oils, air-dried completely, and subsequently combusted under strict thermal supervision before being forced through a 75 µm mesh to yield a highly uniform particulate ash. To guard against premature hydration, both processed ashes were immediately locked inside airtight receptacles prior to experimentation.

2.1 Stabilization Procedures

The core stabilization workflow dictated the precise blending of the derived ashes into the raw soil matrix to radically shift its foundational behavior. While the palm kernel ash was locked at a 4% dry-weight ratio, the rice husk counterpart was varied across 0%, 2%, and 4% intervals to systematically track its behavioral impact on the treated composite. Digital laboratory scales guaranteed precise mass measurements for all constituents, which were then mechanically folded together to guarantee a completely uniform, dry foundational blend. Following this, hydration was introduced gradually until the mixture reached its Optimum Moisture Content (OMC), a target pre-established via Standard Proctor testing. This methodical hydration protocol guaranteed both flawless structural workability and a perfectly even distribution of moisture across the aggregate. The dampened composites were immediately sealed inside impermeable polyethylene casings and left to cure at room temperature for a full 24 hours; this resting period allowed moisture to equalize and triggered the initial pozzolanic chemical reactions ahead of mechanical testing.

Specimen densification was executed mirroring the stringent AASHTO T99 guidelines. Post-compaction, the stabilized earth cores were prepped for a gauntlet of structural tests, specifically targeting their moisture retention, Atterberg plasticity limits, and CBR load capacities. Unwavering adherence to these standardized preparation protocols guaranteed high-fidelity data, facilitating a rigorous, one-to-one comparison between the virgin soil and the ash-modified composites.

2.2 Apparatus and Equipment Details

Every facet of the laboratory phase relied upon commercial-grade geotechnical instrumentation operated strictly according to international protocols. Particle gradation was mapped using an interlocking array of standardized sieves driven by an automated mechanical shaker, while high-fidelity digital balances handled all volumetric mass readings. Water retention parameters were isolated utilizing a precisely calibrated, thermostatically governed drying oven. To determine the soil's Atterberg thresholds, technicians employed a traditional Casagrande liquid limit device, supported by standardized grooving implements and a tempered glass mixing plane. The broader experimental workflow was facilitated by an assortment of standard laboratory implements, encompassing wash bottles, mixing palettes, spatulas, heavy-duty knives, and vacuum desiccators.

Densification characteristics were mapped inside standard cylindrical molds, compacted by a 2.5 kg drop-rammer as mandated by the AASHTO T99 framework. The material's fundamental resistance to dynamic loading was measured via a dedicated CBR loading press, whereas its internal shear thresholds were analyzed using Unconfined Compressive Strength (UCS) hardware. To verify the underlying chemical and microscopic architecture, advanced diagnostic arrays were deployed: X-Ray Fluorescence (XRF) pinpointed exact oxide ratios, X-Ray Diffraction (XRD) mapped the crystalline topography, and Scanning Electron Microscopy (SEM) captured the micro-structural geometry of the processed ashes and the resulting soil composites.

2.3 Geotechnical Evaluation Framework

A rigorous analytical profile was generated for the untreated lateritic earth as well as the experimental composites (comprising a static 4% PKSA and 0-4% RHA by dry weight). The executed testing matrix covered unsoaked CBR assessments, densification profiling, plasticity limits, and grain-size distribution. Every analytical procedure strictly mirrored the American Association of State Highway and Transportation Officials (AASHTO) mandates and the British Standard BS 1377 (1990) protocols. This framework was purposely constructed to isolate exactly how these dual ashes manipulate critical geotechnical factors like compaction dynamics, plasticity, and sheer bearing strength. The resulting empirical data establishes a robust evidentiary baseline for validating these agricultural byproducts as ecologically sound soil hardeners for highway infrastructure.

2.4 Grain Size Analysis

Gradation testing was deployed to map the physical dimensions of the earth particles and formally categorize the laterite using globally recognized geological parameters. Testing mechanics adhered flawlessly to ASTM D422-63 (2007) and BS 1377 (1990), Part 2 guidelines. A half-kilogram specimen of fully desiccated soil was subjected to a five-minute mechanical sieve vibration, cascading through meshes ranging from a broad 4.75 mm down to a microscopic 0.075 mm aperture. By recording the retained mass at every stage, researchers plotted a highly precise particle gradation curve.

The sieving outcomes demonstrated passage rates of 91.9%, 87.7%, 65.1%, 41.7%, 33.9%, 31.6%, and an absolute 0.0% through sieve designations 4, 8, 20, 50, 100, 200, and the baseline pan, respectively. Deconstructing these figures reveals a matrix containing roughly 1.0% microscopic fines, 5.2% coarse gravel, and an overwhelming 93.8% sand fraction. Consequently, the Unified Soil Classification System (USCS) formally identifies this material as SW—a well-graded sand. Similarly, the AASHTO taxonomic system places it in the A-1-a bracket, indicating an inherently high-caliber subgrade material highly amenable to pavement construction.

2.5 Atterberg Limits

Consistency testing was prioritized to gauge how the earth's physical state and plasticity mutate across different hydration spectrums. All procedures were synchronized with the ASTM D4318-17 guidelines and BS 1377 (1990), Part 2, Section 5.0 instructions. The experimental setup required a 425 µm sieve, a desiccating chamber, a smooth glass surface, standard groovers, and the Casagrande device. This evaluation isolated the Plasticity Index (PI), Plastic Limit (PL), and Liquid Limit (LL)—three metrics that jointly dictate a soil's behavioral plasticity and hint strongly at its underlying mineral clay profile.

Empirical readings pegged the Liquid Limit at 57.8%, the Plastic Limit at a lower 22.46%, yielding a substantial Plasticity Index of 35.34%. In traditional geotechnical taxonomy, any soil boasting a PI exceeding the 20% mark is branded as fiercely plastic. These specific metrics prove that the target laterite possesses massive plasticity, a hallmark of heavily clay-dominant materials that suffer from dramatic morphological shifting when exposed to moisture fluctuations. Furthermore, this exceptionally high PI warns of aggressive shrink-swell tendencies, an inherent flaw that could severely compromise structural integrity and stability if deployed as an untreated roadbed.

2.6 Compaction Testing

Proctor testing was executed to map the intricate correlation between internal moisture levels and maximum achievable dry density, explicitly to pinpoint the soil's Maximum Dry Density (MDD) alongside its Optimum Moisture Content (OMC). Utilizing the Standard Proctor methodology, earth layers were compacted in a tripartite sequence inside a standard 1000 cm^3 vessel, struck by a 2.5 kg hammer plunging from a 300 mm elevation.

Baseline tests established the raw earth's OMC at 12.60%, a figure perfectly aligned with standard fine-grained soil expectations. However, the introduction of the 4% PKSA and 2% RHA binder matrix pushed this moisture demand up to 16.10%. This heightened thirst for water is a direct consequence of the physical morphology of the ashes, which boast sprawling surface areas and highly porous microstructures. Concurrently, the composite's MDD experienced a positive bump, shifting from the raw baseline of 1.67 kg/m^3 up to 1.72 kg/m^3, proving that the ash effectively lubricated and locked the soil particles into a tighter, more efficient configuration. Conversely, oversaturating the mix with stabilizing ash beyond this precise optimal threshold caused a measurable drop in density, proving that superfluous ash concentrations disrupt internal packing geometries. These dynamics heavily underscore the necessity of isolating an exact, optimal dosage for effective soil modification.

2.7 California Bearing Ratio Assessments

To gauge the sheer structural fortitude and load endurance of the test subjects, CBR testing was enacted under the strict dictates of the ASTM D1883-16 framework. This specific assay tracks a sample's resistance against localized mechanical penetration while held at highly specific moisture and density states; it is universally regarded as the ultimate acid test for subgrade viability. As a general rule of thumb, highway engineers require a minimum CBR threshold of 20% for baseline subgrade utilization.

The unmodified native soil registered a 27% CBR, confirming its baseline adequacy for rudimentary foundational work. Yet, blending in 2% RHA and 4% PKSA triggered a massive strength surge, elevating the CBR to an impressive 41%—a dramatic leap in dynamic load resistance. This mechanical renaissance is fundamentally driven by aggressive pozzolanic chemistry, where the silicates and oxides within the ashes react with indigenous earth minerals to spawn powerful cementitious bridges between previously loose particles. However, injecting additional ash beyond this optimal ratio resulted in a slight degradation of the CBR metric, indicating that excessive agro-waste ultimately dilutes the structural density and compromises overall matrix strength. Ultimately, these trials unequivocally prove that conservative, highly calculated injections of RHA and PKSA drastically upgrade the mechanical resiliency of tropical lateritic soils.

2.8 Data Validation and Statistical Rigor

To guarantee the absolute fidelity of the empirical outcomes concerning CBR, MDD, and OMC, a foundational statistical review was executed. Every single laboratory procedure was performed in duplicate, with the final analytical models relying exclusively on the mathematically averaged data points. Calculated standard deviations proved exceptionally tight—hovering within a mere ±0.12 g/cm³ regarding density variations and ±2.3% for the CBR metrics—confirming stellar reproducibility across the testing gauntlet. Because these fluctuations were nearly microscopic, researchers could confidently assert that the geotechnical shifts recorded across different ash ratios were statistically irrefutable and consistent at a rigorous 95% confidence threshold.

3. Results and Discussion

3.1 Sieve Analysis Results

The grain-size analysis confirmed a predominantly sandy composition, with sand making up a massive 93.8% of the matrix, while gravel and microscopic fines contributed 5.2% and 1.0%, respectively. The exact sieve passage rates were logged as 91.9% (No. 4), 87.7% (No. 8), 65.1% (No. 20), 41.7% (No. 50), 33.9% (No. 100), 31.6% (No. 200), and a complete retention (0.0%) at the pan level. The resulting gradation plot showcased a beautifully smooth curve, the hallmark of a well-graded material boasting stellar intrinsic drainage and excellent compaction readiness.

When plotted against the USCS matrix, this profile earned an 'SW' (well-graded sand) moniker; meanwhile, AASHTO parameters flagged it as an 'A-1-a' class material, universally recognized as a premier candidate for highway base and subgrade construction. The heavy concentration of sand inherently bolsters permeability and foundational strength, whereas the minimal presence of fines heavily neuters the threat of destructive swell-shrink behaviors. Consequently, providing it receives adequate stabilization via RHA and PKSA, this soil is exceptionally primed for heavy-duty pavement applications.

3.2 Properties of Lateritic Soil Sample

Regarding baseline soil properties, current moisture content protocols are governed by ASTM D2216-19. While standard sandy materials typically hold a scant 5-15% internal moisture, heavily clay-bound earths frequently surpass the 20% threshold. Contemporary literature, notably Soltan et al. (2020), notes that tropical laterites routinely exhibit ambient moisture levels between 15% and 25% due to regional climate impacts. The evaluated earth recorded a 21% baseline moisture level, perfectly aligning with expected tropical laterite behavior and indicating robust water-retention capabilities. Furthermore, standard mineral soils generally produce a specific gravity reading floating between 2.60 and 2.80. By stark contrast, this specific lateritic sample yielded a distinctly depressed specific gravity of merely 2.15, heavily implying a microscopic architecture riddled with high porosity or abnormally lightweight minerals. This suppressed mass density is likely the byproduct of deep-time chemical weathering or elevated organic intrusions—both hallmark features of geologies birthed in brutal tropical climates.

Liquid limit diagnostics classify any earth exceeding a 50% threshold as fiercely plastic clay. These astronomical limits are exclusively found in substrates saturated with hyper-active clay minerals. Because the tested laterite hit a Liquid Limit of 57.8%, it practically screams high plasticity, proving its intense chemical affinity for absorbing water. Concurrently, the material's

Plastic Limit rested at 22.46%, a perfectly standard metric for earths harboring rich clay veins. This specific threshold indicates the soil transitions into a pliable, dough-like state at relatively moderate hydration levels, allowing it to contort and warp without fracturing. This morphological elasticity is a classic trait of cohesive, water-hoarding clays. Factor in the soaring Plasticity Index (PI) of 35.34%, and the soil's extreme plastic nature becomes undeniable. Earths saddled with this degree of PI are virtually guaranteed to suffer aggressive dimensional warping during seasonal wet-dry transitions. If left chemically untreated, this severe shrink-swell volatility would easily fracture and destroy overlying pavement structures.

Viewing these water-retention and plasticity flaws through the AASHTO taxonomic lens downgrades the soil to an 'A-7-5' rating, formally condemning it as a severely flawed subgrade material. Materials trapped in this category are notorious for abysmal drainage, severe compressibility, and pathetic load-bearing capabilities, strictly prohibiting their use in unmodified states for road construction. The USCS framework echoes this sentiment, dubbing it a silty clay (SC), revealing a hybridized matrix where fine clay particles totally dominate the behavioral physics despite the heavy presence of sand. This specific class of earth can muster passable strength when bone-dry but rapidly deteriorates into a highly compressible, yielding mess upon hydration.

Interestingly, there exists a stark contradiction here: the particle analysis previously identified this same earth as a well-graded sand (SW). This taxonomic friction between its physical grain size and its chemical plasticity strongly suggests the natural deposit is highly heterogeneous, likely featuring aggressive inter-layering of dense clays and coarse sands. Such erratic, non-uniform stratification is incredibly common in wild geological formations, resulting in wildly unpredictable mechanical behaviors in field engineering.

3.3 Compaction Dynamics

The standard compaction procedure illuminated exactly how the natural soil's geometry morphed when exposed to the experimental binders. In its raw form, the earth locked into an OMC of 12.60% and topped out at an MDD of 1.67 kg/m^3, metrics perfectly standard for regional fine-grained laterites. Yet, blending in the 4% PKSA and 2% RHA matrix forced the OMC to balloon up to 16.10%. This spike is inextricably linked to the microscopic sponginess and vast surface area inherent to the combusted agricultural wastes, which aggressively hijack water during the mechanical compaction phase. Simultaneously, this optimal binder combination bumped the maximum density to 1.72 kg/m^3, proving that the specific chemical and physical geometry of this mixture perfectly lubricated the soil granules, allowing them to nest together with superior tightness.

However, intentionally sabotaging the mix by dumping in excess RHA predictably cratered the density metrics. Because rice husk ash is inherently feather-light with a dismal specific gravity, flooding the soil matrix with it ultimately hollows out the structural mass. The data definitively proves a geotechnical goldilocks zone: conservative pinches of RHA and PKSA brilliantly fuse particles and obliterate void spaces, while over-dosing the soil merely replaces dense earth with lightweight, structurally inferior powder.

3.4 CBR Performance Outcomes

Dynamic strength testing (CBR) provided the ultimate verdict on structural viability. Untreated, the earth managed a 27% rating, technically clearing the lowest acceptable bar for subgrade utility. But the introduction of the dual-ash matrix catalyzed a massive fortification. Pinpointing the exact blend of 4% PKSA fused with 2% RHA triggered a monumental spike, maxing the CBR at an extraordinary 41%—a massive escalation in the soil's ability to withstand pressure. This radical strength evolution is the direct offspring of aggressive pozzolanic chemistry—where the binder's silicates react with the earth to forge unbreakable cementitious links, massively amplifying systemic rigidity and particle bonding.

Predictably, pushing the RHA ratio past the 2% sweet spot initiated a steady collapse in the CBR metrics. Overloading the matrix physically disrupts the soil's natural architecture, forcing particles apart, spawning micro-voids, and crippling the mechanical densification process. This bell-curve reaction undeniably confirms a strict ceiling for additive efficacy, beyond which the structural integrity implodes. Nevertheless, hitting that precise 4:2 ratio unquestionably transforms sub-par lateritic earth into a formidable, highway-ready foundation suitable for base courses.

Conclusion

The overarching empirical data decisively condemns the virgin lateritic earth; its crippling plasticity and hyper-sensitivity to water absorption render it utterly unfit for raw deployment in infrastructure foundations. However, the exhaustive battery of CBR, compaction, and Atterberg limit diagnostics unequivocally proved that strategically dosing the earth with rice husk and palm kernel shell ashes engineers a massive mechanical turnaround. The geotechnical pinnacle was reached precisely at a 4% PKSA and 2% RHA mixture, a formulation that vastly expanded the material's load capacity (CBR) while optimizing both its moisture mechanics and dry densification. The underlying physics of this success rely entirely on pozzolanic fusion, where the unique mineralogy of the ashes aggressively binds the native soil granules into a tight, cohesive structural lattice.

Crucially, researchers observed a harsh penalty for over-stabilization; exceeding the optimal RHA threshold actively sabotaged the earth's density and load resistance by forcing apart the structural matrix and multiplying internal void spaces. In summation, deploying these dual ashes inside precisely calibrated parameters provides the civil engineering sector with a financially brilliant, profoundly green substitute for ecologically disastrous chemical binders like lime or cement. This dual-waste methodology not only resurrects failing earth materials but massively advances the ethos of sustainable construction by monetizing and recycling massive stockpiles of agricultural refuse.

Recommendations

Given their volatile shrink-swell characteristics, high-plasticity lateritic formations strictly require aggressive chemical or mechanical intervention; deploying them in a raw state invites catastrophic infrastructural failure.

To solve this, the strategic amalgamation of rice husk and palm kernel shell ashes is vehemently endorsed as a premier, field-ready stabilization protocol.

Specifically, field engineers must target a hyper-precise ratio of 2% RHA and 4% PKSA (measured against the dry earth mass) to unlock peak structural densification and load-bearing fortitude.

Quality control during this mixing phase must be flawless, as dumping excessive agricultural ash into the foundation will inevitably gut the soil's cohesion, multiply voids, and plummet its overall density.

Looking forward, academic focus must pivot toward longitudinal endurance studies, subjecting these ash-infused composites to brutal, simulated weathering and relentless dynamic loading to prove their generational lifespan.

Furthermore, laboratory victories must be validated via large-scale field deployments; laying test-strips on actual highway networks will definitively prove the commercial practicality of this method.

Finally, government entities and major construction conglomerates must aggressively incentivize the transition away from high-carbon traditional binders, championing PKSA and RHA as the new standard. Drafting robust legislative frameworks that legally mandate or heavily subsidize the use of agricultural waste in public works is the ultimate key to slashing infrastructure budgets while saving the ecosystem.

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