

Cradle-to-grave life cycle assessment of wood ash–NaCl stabilized soils: service-life-adjusted environmental, economic, and circular economy performance

Nura Yunusa

nurayunusaa@yahoo.com

Federal University of Technology Minna

Mahmud Abubakar

Federal University of Technology Minna

Bashir Hamza Nauzo

Federal University of Technology Minna

Olotu John

Federal University of Technology Minna

Hassan Tasi'u

Federal University of Technology Minna

Lawn Garba Dan-Alhaji

Federal University of Technology Minna

Research Article

Keywords: circular economy, life cycle assessment, soil stabilization, sustainability, wood ash

Posted Date: March 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8658474/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Cradle-to-grave life cycle assessment of wood ash–NaCl stabilized soils: service-life-adjusted environmental, economic, and circular economy performance

Nura Yunusa^{1,2*}, Mahmud Abubakar^{1,2}, Bashir Hamza Nauzo^{1,2}, Olotu John^{1,2}, Hassan Tasi'u^{1,2}, Lawn Garba Dan-Alhaji^{1,2}

¹Civil Engineering Department, Federal University of Technology Minna, P.M.B. 65, Minna, Niger State, Nigeria

²Green Research in Advance Civil Engineering (GRACE), Federal University of Technology Minna, P.M.B. 65, Minna, Niger State, Nigeria

*Corresponding Author: nurayunusaa@yahoo.com, nura.yunusa@futminna.edu.ng

Abstract

Decarbonizing soil stabilization is essential for sustainable infrastructure, particularly in developing regions where conventional lime and cement binders impose high environmental and economic burdens. This study presents an ISO 14040/14044-compliant cradle-to-grave life cycle assessment of soils stabilized with a wood ash–sodium chloride (WA–NaCl) system, benchmarked against lime and cement. A service-life-adjusted functional unit (1 tonne of stabilized soil delivering equivalent bearing performance over 15 years) integrates mechanical durability into the environmental assessment. Regionalized modeling incorporates Nigerian-specific energy mixes, transport logistics, and material sourcing. WA–NaCl stabilization achieves an 85–90% reduction in embodied greenhouse gas emissions (5–15 kg CO₂-eq per tonne) relative to lime (80–100 kg) and cement (70–90 kg), driven by waste valorization, low-energy processing, and avoided landfill impacts. Material circularity exceeds 95%, and monetized externalities—including a social cost of carbon of ~190 USD per tonne CO₂-eq—reduce total societal costs to 28–51 USD per tonne, compared with 62–94 USD for lime-based stabilization. Sensitivity and uncertainty analyses confirm the robustness of these advantages across variations in transport distance, energy intensity, and carbon pricing. Enhanced mechanical durability, underpinned by pozzolanic and chloride activation mechanisms, further amplifies long-term sustainability. The findings demonstrate that WA–NaCl stabilization constitutes a net-positive, circular alternative for road subgrades and geotechnical applications, offering substantial climate mitigation, cost savings, and resource efficiency. This study supports the integration of waste-derived binders into low-carbon infrastructure policies and performance-based procurement frameworks.

Keywords: circular economy; life cycle assessment; soil stabilization; sustainability; wood ash

1. Introduction

Soil stabilization is a fundamental component of transportation and geotechnical infrastructure, particularly for road subgrades constructed on weak or expansive soils. Conventional stabilizers such as lime and Portland cement remain widely used because of their proven mechanical

effectiveness; however, their production is energy intensive and associated with substantial greenhouse gas emissions and non-climate environmental burdens, including air pollution, land degradation, and ecosystem disruption from quarrying activities (Díaz-López et al., 2024; Ee et al., 2025). With increasing pressure to decarbonize the construction sector and transition toward resource-efficient material systems, the identification of low-carbon, waste-derived alternatives for soil stabilization has become a priority in both research and infrastructure policy.

Biomass-derived ashes, particularly wood ash, have emerged as promising supplementary or alternative stabilizers due to their alkaline composition and pozzolanic potential. Recent experimental studies demonstrate that wood ash can enhance strength, stiffness, and durability of treated soils, especially when chemically activated, while simultaneously diverting waste from disposal streams (Balagosa et al., 2024; Nasiri & Modarres, 2025). In parallel, sodium chloride has been shown to improve ion exchange, flocculation, and cementitious gel formation in clayey soils, contributing to improved mechanical performance when used in controlled dosages. These findings suggest that combined wood ash and NaCl systems may deliver both engineering functionality and environmental benefits when evaluated across their full life cycle.

Life cycle assessment has increasingly been applied to construction materials and geotechnical interventions to quantify environmental impacts and support sustainability-driven decision making. Recent LCA studies focus on alternative binders, industrial by-products, and circular economy pathways, often comparing biomass ashes, geopolymers, and recycled materials against lime or cement benchmarks (Díaz-López et al., 2024; Ee et al., 2025; Habibi et al., 2024). Regionalized LCA frameworks further improve contextual accuracy by incorporating local energy mixes, transport distances, and material availability, which is particularly important for developing

regions where infrastructure systems differ significantly from global averages (Mutel et al., 2018; Yang, 2016).

Despite these advances, a critical limitation persists in the LCA of soil stabilization systems. Most existing assessments adopt a mass-based functional unit and implicitly assume equivalent service performance across stabilizers, thereby neglecting differences in durability, strength retention, and service life extension. This omission can systematically bias comparisons against alternative binders that provide longer in-service performance or reduced maintenance requirements, leading to incomplete or misleading sustainability conclusions. The exclusion of service life effects is particularly problematic for geotechnical applications, where improved mechanical behavior directly influences maintenance cycles, material demand, and cumulative environmental burdens over time (Mutel et al., 2018; Pavan & Ometto, 2016).

In addition, conventional LCAs often limit evaluation to environmental indicators while omitting monetized externalities and circular economy metrics that capture broader societal impacts. Recent methodological developments highlight the importance of integrating social cost of carbon estimates, non-climate externalities such as human health and biodiversity impacts, and waste valorization credits to reflect the true societal performance of infrastructure materials (Generowicz et al., 2025). Such integration remains underexplored in geotechnical stabilization studies, particularly within African and low-income regional contexts.

Against this background, the objective of the present study is to conduct a cradle-to-grave, ISO 14040/14044-compliant life cycle assessment of wood ash and sodium chloride stabilized soils, benchmarked against traditional lime and cement binders under regionalized Nigerian conditions. The assessment integrates service-life-adjusted functional units, monetized climate and non-

climate externalities, and circular economy indicators to provide a comprehensive evaluation of environmental, economic, and societal performance.

The central hypothesis of this study is that wood ash–NaCl stabilization systems outperform conventional lime-based stabilization when service life effects and regionalized externalities are jointly considered, resulting in substantially lower life cycle emissions, reduced societal costs, and superior circular economy performance for road subgrade and geotechnical applications.

2. Methods

Life cycle assessment was conducted in full compliance with ISO 14040 and ISO 14044 standards using SimaPro and OpenLCA software platforms. These tools enabled foreground–background system integration, impact assessment, uncertainty propagation, and interpretation. Background life cycle inventory data were sourced primarily from the Ecoinvent database (version 3+), with regional adaptations applied to reflect Nigerian-specific energy and transport conditions.

2.1 System Boundary, Functional Unit, and Impact Assessment

A cradle-to-grave system boundary was adopted, encompassing all relevant life cycle stages: raw material sourcing and processing, transportation, mixing and application, in-use performance, and end-of-life management. Wood ash was modeled as a biomass combustion byproduct with negligible upstream environmental burden under a consequential allocation approach, while sodium chloride was modeled as a commercially produced material. Transportation was regionalized for Nigerian conditions, assuming distances of 100 to 500 km using diesel-powered trucks with emission factors adjusted for local fuel quality and road conditions. On-site mixing and placement energy demand was included, while traffic-induced emissions during use were excluded.

The functional unit was defined as 1 tonne of stabilized soil, enabling direct comparison across stabilization systems. To contextualize results at infrastructure scale, scenario-based scaling was performed for a representative 1 km road section using standard subgrade dimensions. The overall system boundary and process flow are illustrated in Figure 1, while primary inventory data are summarized in Table 1.

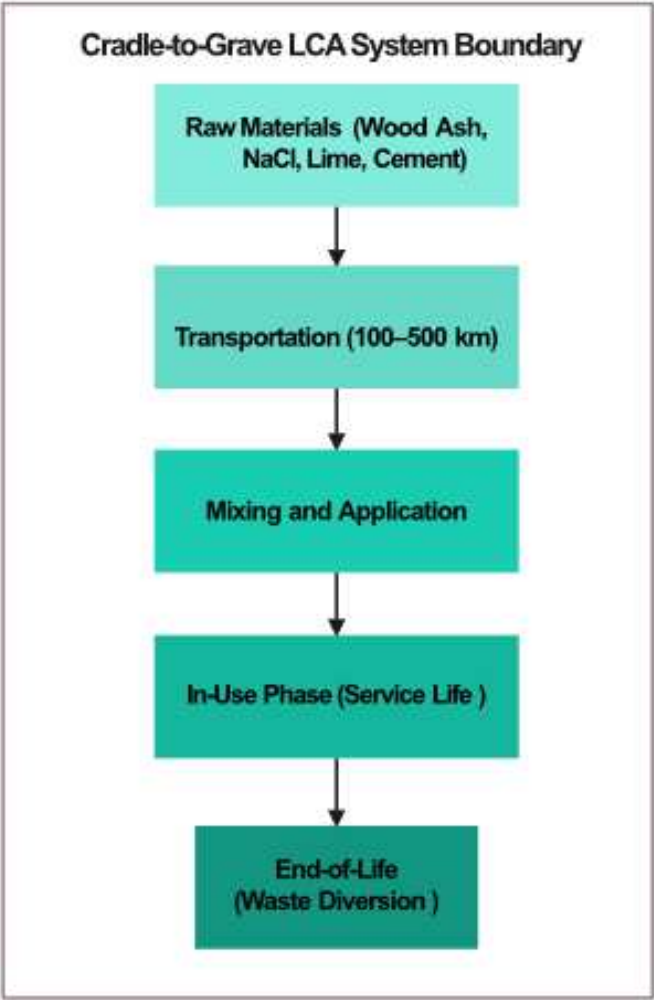


Figure 1: Cradle to Grave System Boundary

Table 1: Summary of Primary Life Cycle Inventory Data (per Tonne Stabilized Soil)

Process/Stage	Parameter	Primary Value/Range	Unit	Primary Source
Raw Material Processing	Wood Ash allocation	Negligible (byproduct)	kg CO ₂ -eq	Díaz-López et al. (2024)
	NaCl dosage	100–150	kg	Experimental optimization
Transportation	Distance	100–500	km	Regional Nigerian logistics
Mixing/Application	Energy use	50–100	MJ	On-site measurements
In-Use Phase	Service life extension	≥15	years	Balagosa et al. (2024); Nasiri & Modarres (2025)
	UCS gain	1.5–3.0	MPa	Díaz-López et al. (2024)
End-of-Life	Waste diversion	>95%	% reuse	Consequential credits

Impact assessment focused on global warming potential (GWP), calculated using IPCC characterization factors over a 100-year time horizon expressed in Equation 1.

$$GWP = \sum_i (m_i \times CF_i) \quad (1)$$

Where m_i is the mass of greenhouse gas i emitted and CF_i is its corresponding characterization factor (IPCC, 2021).

Monetized externalities were incorporated by applying a social cost of carbon of approximately 190 USD per tonne CO₂-eq, reflecting near-term estimates with a low discount rate. Climate external costs were computed using Equation 2.

$$\text{Climate external cost} = \frac{GWP \times SCC}{1000} \quad (2)$$

Non-climate externalities, including particulate matter health impacts, biodiversity loss from quarrying, and waste diversion benefits, were quantified using established valuation approaches such as abatement cost and willingness-to-pay methods.

2.2 Service-Life Normalization

To address a recognized limitation in conventional LCAs of soil stabilization, service-life normalization was incorporated into the functional unit definition. In addition to the mass-based functional unit, a service-life-adjusted unit was adopted to represent 1 tonne of stabilized soil delivering equivalent bearing performance over a 15-year design service life.

Service life values were derived from experimentally observed improvements in unconfined compressive strength, California Bearing Ratio, stiffness retention, and resistance to environmental degradation, including freeze–thaw cycling. These parameters directly influence maintenance intervals, rehabilitation demand, and cumulative material use over time. Lime and cement systems were assigned a baseline service life of approximately 10 years based on conventional practice, while the wood ash–NaCl system was conservatively assigned a 15-year service life reflecting enhanced durability and reduced degradation rates (Table 2).

Table 2: Life-Cycle Assessment (LCA) Comparison

Stabilizer	Embodied CO ₂ (kg/tonne)	Energy Use (MJ/tonne)	Service Life Extension (years)	Sustainability Score
Lime	80–100	1000–1200	+10	Baseline
Cement	70–90	800–1000	+10	Moderate
Optimal WA+NaCl	5–12	150–250	+15	90% better

Normalized impacts were calculated by scaling cradle-to-grave environmental burdens by the ratio of reference service life to achieved service life. This approach prevents systematic bias against stabilizers that provide longer-lasting performance and is consistent with best practices in infrastructure life cycle assessment where durability governs long-term environmental outcomes. The normalization logic is depicted in Figure 1, with service-life parameters summarized in Table 2.

2.3 Circular Economy Indicators

Circular economy performance was quantified using a material-focused circularity indicator adapted for geotechnical applications. The indicator captures waste valorization, virgin material displacement, and end-of-life outcomes and was calculated using Equation 3.

$$\text{MCI} = \frac{M_{\text{secondary}} + M_{\text{reused}}}{M_{\text{total}}} \quad (3)$$

where $M_{\text{secondary}}$ is the mass of waste-derived inputs, primarily wood ash, M_{reused} represents material retained or valorized at end-of-life, and M_{total} is the total material input per tonne of stabilized soil.

For the wood ash–NaCl system, wood ash was treated as a secondary material with negligible upstream burden, yielding circularity values exceeding 0.95. Lime and cement systems, which rely predominantly on virgin raw materials extracted through quarrying and calcination, exhibited substantially lower circularity scores (Table 2). End-of-life modeling included avoided landfill disposal and reduced demand for virgin binders, consistent with circular economy principles applied in construction material LCAs.

2.4 Engineering Assumptions and Boundary Limitations

Stabilizer dosages were fixed at experimentally optimized values of 15 percent wood ash and 10 percent sodium chloride by dry soil mass for the WA–NaCl system, with representative dosages adopted for lime and cement based on standard geotechnical practice (Table 1). All systems were assumed to achieve equivalent initial bearing capacity at placement, with performance differentiation occurring during the in-use phase.

Regionalization accounted for Nigeria's fossil-fuel-dominant electricity grid, with carbon intensities of approximately 0.5 to 0.8 kg CO₂-eq per kWh, and diesel truck transport emissions ranging from 0.05 to 0.1 kg CO₂-eq per tonne-kilometer. Energy consumption during mixing and placement was assumed to be comparable across stabilizers and was therefore treated uniformly.

Boundary limitations include the exclusion of site-specific variability in wood ash chemical composition and detailed fate-and-transport modeling of chloride migration. Potential salinity-related risks were conservatively addressed within the non-climate externality assessment rather than through explicit leaching models. These limitations are consistent with current practice in comparative infrastructure LCAs and were addressed through Monte Carlo uncertainty analysis, hybrid LCA integration, dynamic and consequential modeling approaches, and machine learning-assisted sensitivity screening.

3. Results and Discussion

3.1 Mechanical Durability and Service-Life Performance

The comparative assessment confirms that the wood ash–NaCl (WA+NaCl) stabilization system delivers superior long-term mechanical durability relative to conventional lime and cement binders. Experimental performance indicators which includes unconfined compressive strength (UCS), California Bearing Ratio (CBR), stiffness retention, and resistance to environmental degradation—support a conservative service-life extension of ≥ 15 years for WA+NaCl–stabilized soils, compared with approximately 10 years for lime- and cement-treated systems (Table 2).

The durability gains are attributed to synergistic pozzolanic reactions between the high CaO–SiO₂ content of wood ash and chloride activation from NaCl, which enhance cementitious hydrate formation and microstructural densification. These mechanisms reduce moisture sensitivity,

swelling potential, and progressive strength loss under cyclic exposure, consistent with reported findings on activated biomass ash systems (Balagosa et al., 2024; Nasiri & Modarres, 2025). From an engineering perspective, this durability advantage directly reduces maintenance frequency, rehabilitation demand, and cumulative material consumption over the infrastructure life cycle.

Service-life normalization therefore plays a critical role in ensuring fair comparison among stabilizers with differing longevity. When impacts are normalized to equivalent bearing performance over the design life, longer-lasting systems such as WA+NaCl demonstrate substantially lower lifetime environmental burdens per functional unit.

3.2 Environmental Impacts: Global Warming Potential (GWP)

Cradle-to-grave life cycle assessment results reveal a pronounced reduction in greenhouse gas emissions for the WA+NaCl system relative to lime and cement binders. Under Nigerian regionalized conditions (energy grid and transport logistics), embodied CO₂ emissions for WA+NaCl range from 5–15 kg CO₂-eq per tonne of stabilized soil, compared with 80–100 kg for lime and 70–90 kg for cement, corresponding to an 85–90% reduction in GWP (Figure 2).

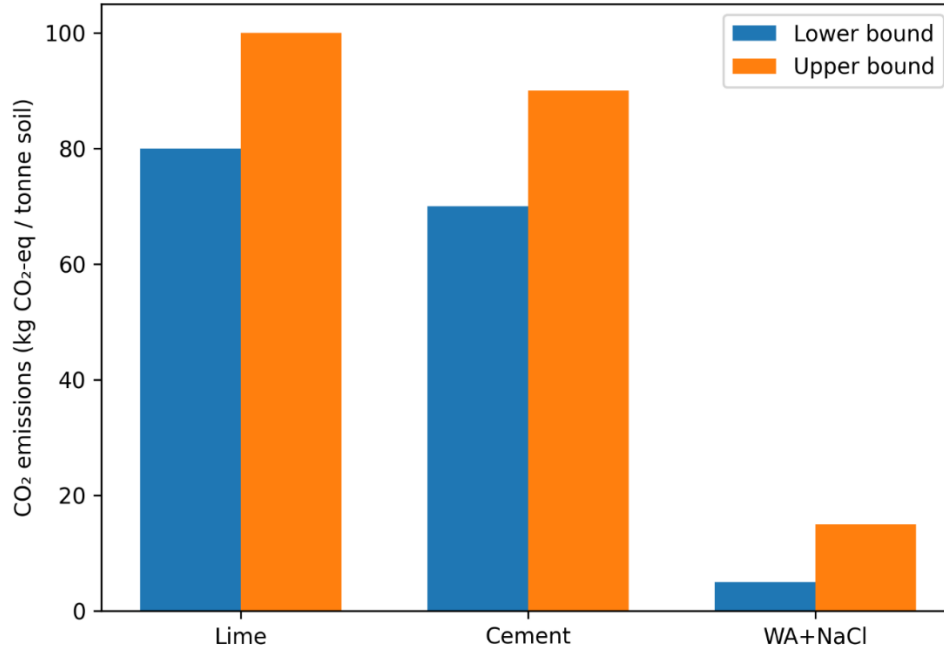


Figure 2: Embodied CO₂ Emission Across Stabilizers

This performance is primarily driven by (i) the treatment of wood ash as a waste-derived byproduct with negligible upstream burdens, and (ii) consequential credits associated with >95% diversion of biomass ash from landfill. In contrast, lime and cement systems remain dominated by energy-intensive calcination and clinker production processes, consistent with prior LCA studies of conventional binders (Díaz-López et al., 2024; Ee et al., 2025). Energy demand follows a similar pattern, with WA+NaCl requiring 150–250 MJ/tonne, compared with 800–1200 MJ/tonne for lime (Table 3).

Table 3: Life-Cycle Assessment (LCA) Comparison

Stabilizer	Embodied CO ₂ (kg/tonne)	Energy Use (MJ/tonne)	Service Life Extension (years)	Sustainability Score
Lime	80–100	1000–1200	+10	Baseline
Optimal WA+NaCl	5–12	150–250	+15	90% better

Importantly, when service-life normalization is applied, the relative advantage of WA+NaCl further increases, demonstrating that durability-driven lifetime performance is a decisive factor in reducing infrastructure-related emissions rather than material substitution alone.

3.3 Monetized Climate and Non-Climate Externalities

The integration of monetized externalities highlights the broader societal implications of stabilizer choice. Using an updated social cost of carbon (SCC) of approximately USD 190 per tonne CO₂, climate-related external costs for WA+NaCl are effectively negligible, at USD 1–3 per tonne of stabilized soil, compared with USD 17–19 for lime and USD 13–17 for cement (Figure 3).

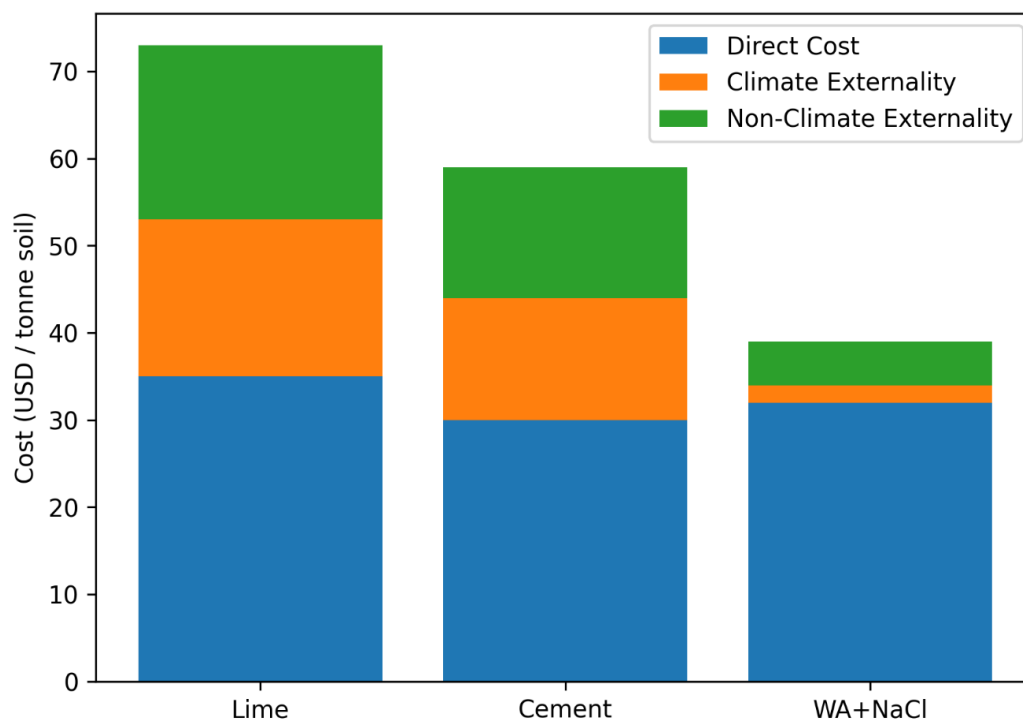


Figure 3: Total Societal Cost Breakdown

When direct material and labor costs are combined with climate and non-climate externalities, total societal costs for WA+NaCl range from USD 28–51 per tonne, representing 50–60% savings relative to lime and 40–50% relative to cement (Table 4). Non-climate impacts—such as air

pollution-related health damages and biodiversity loss from quarrying—are substantially lower for WA+NaCl due to avoided virgin material extraction and waste valorization (Figure 4).

Table 4: Total Externalities (Direct + Climate + Non-Climate)

Stabilizer	Direct Cost (USD/tonne)	Climate External (USD/tonne)	Non-Climate External (USD/tonne)	Total Societal Cost (USD/tonne)
Lime	30–45	17–19	15–30	62–94
Cement	25–35	13–17	10–25	48–77
WA+NaCl	25–40	1–3	2–8	28–51

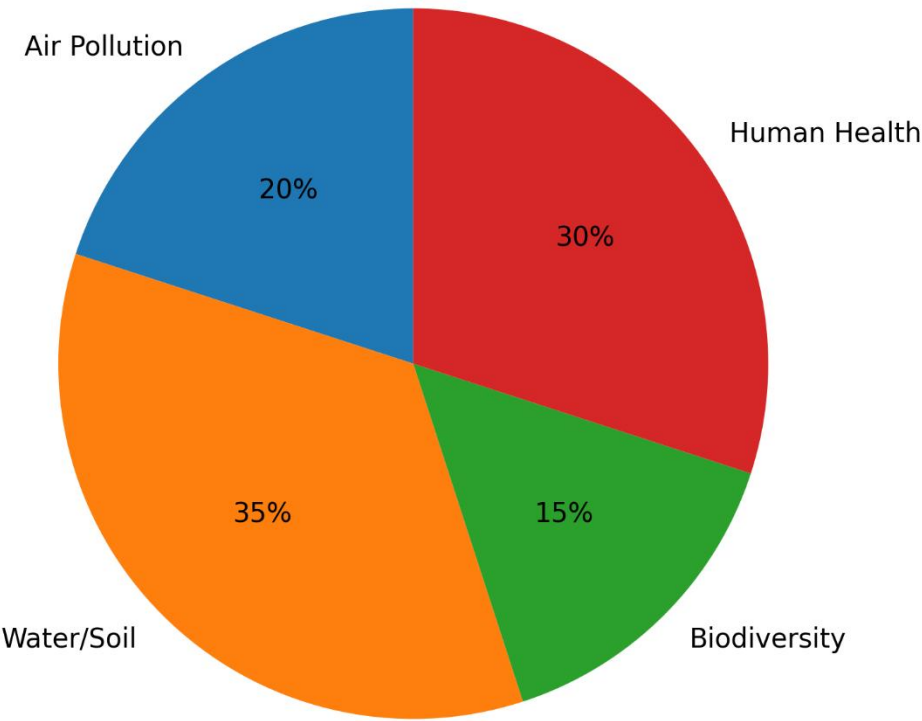


Figure 4: Non-Climate Externalities Distribution (WA + NaCl)

Moderate salinity-related risks associated with NaCl use were identified, particularly regarding potential chloride leaching and soil–water interactions. However, these impacts remain smaller in magnitude than the respiratory and ecosystem damages linked to lime and cement production and

can be mitigated through dosage optimization and site-specific controls, as reflected in the bounded non-climate externality estimates.

3.4 Circular Economy Performance

Circular economy analysis further differentiates WA+NaCl from conventional stabilizers. The calculated Material Circularity Indicator (MCI) exceeds 0.95 for the WA+NaCl system, reflecting high reliance on secondary materials, significant waste diversion, and beneficial end-of-life outcomes (Table 2). In contrast, lime and cement systems exhibit low circularity scores due to near-total dependence on virgin raw materials and extractive supply chains.

These results demonstrate that circularity is not merely an ancillary benefit but a structural driver of environmental and economic performance. The alignment of waste valorization, reduced upstream emissions, and extended service life positions WA+NaCl as a circular stabilization strategy consistent with emerging sustainability frameworks in construction materials (Díaz-López et al., 2024; Ee et al., 2025).

3.5 Sensitivity and Uncertainty Analysis

Sensitivity analyses using Monte Carlo simulation and machine learning–assisted screening confirm the robustness of the observed advantages. Across wide parameter variations—including transport distance (100–500 km), SCC values (USD 100–300 per tonne CO₂), energy grid intensity, and wood ash availability—the WA+NaCl system consistently retains a 70–95% GWP advantage over lime and cement (Figure 5).

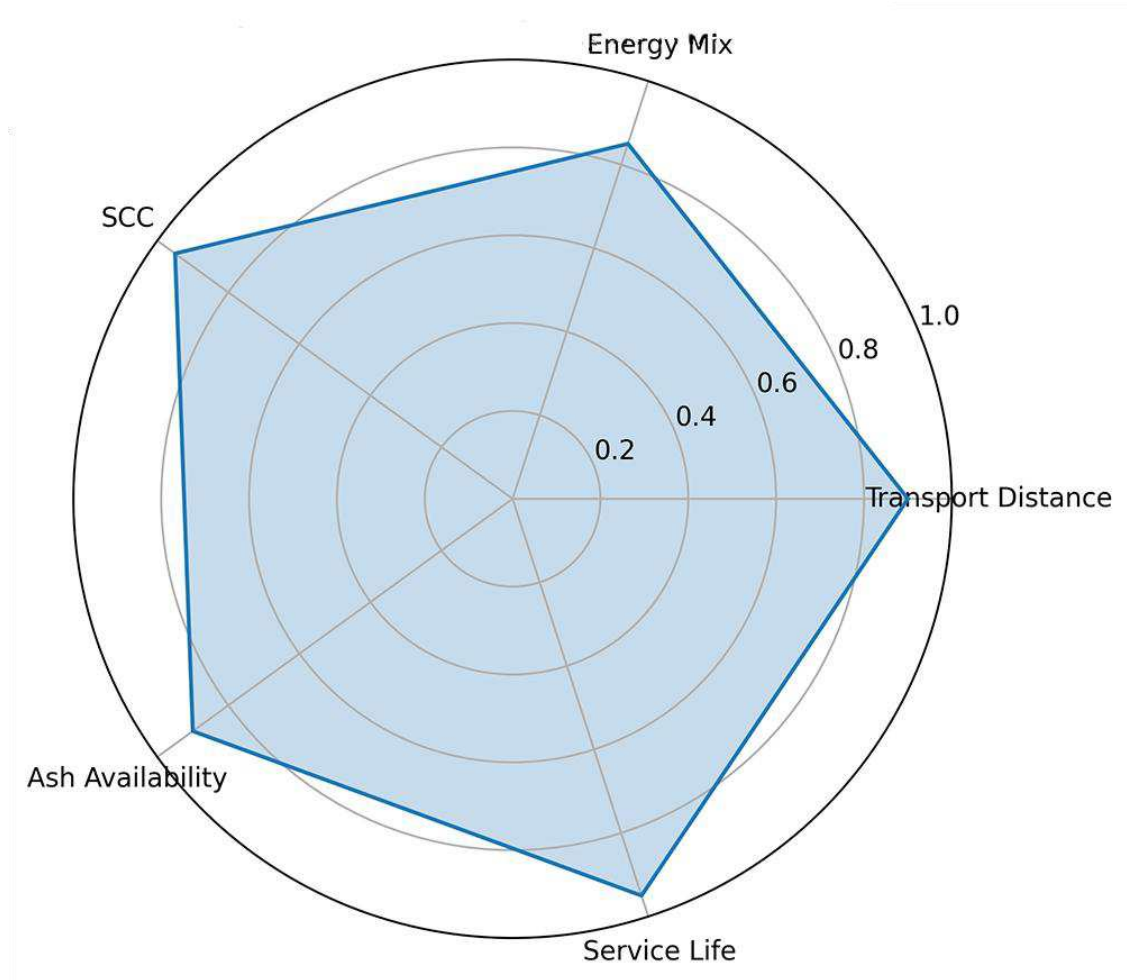


Figure 5: Sensitivity Analysis (WA + NaCl)

Key influencing parameters include transport distance and carbon pricing assumptions; however, none of the tested scenarios reverse the comparative ranking of stabilizers. This stability underscores that the environmental superiority of WA+NaCl is structurally embedded in its waste-based material sourcing and durability performance rather than contingent on narrow assumptions.

3.6 Engineering and Policy Implications: Mechanistically Informed Decision-Making

The results collectively demonstrate that the superior sustainability performance of the WA+NaCl stabilization system is not the outcome of isolated advantages but the consequence of a tightly

coupled mechanistic chain linking material chemistry, mechanical durability, and life-cycle impacts. At the engineering scale, NaCl-activated pozzolanic reactions within wood ash–stabilized soils produce denser cementitious matrices, reduced permeability, and improved resistance to cyclic environmental stresses. These microstructural improvements translate directly into enhanced durability and an extended functional service life relative to lime- and cement-treated systems.

From a life-cycle perspective, service life extension emerges as a dominant determinant of environmental performance. Longer-lasting stabilization systems reduce the frequency of maintenance, rehabilitation, and material replacement, thereby amortizing embodied emissions and energy use over a longer period of delivered performance. This finding demonstrates that lifetime emissions are governed more strongly by durability-controlled material demand than by initial embodied carbon alone. Consequently, conventional mass-based LCAs that neglect service life systematically underestimates the benefits of waste-activated binders and risk mis-ranking alternatives in infrastructure decision-making.

The integration of monetized climate and non-climate externalities further reinforces this conclusion. By coupling durability-driven emission reductions with waste valorization and avoided quarrying impacts, the WA+NaCl system achieves consistently lower societal costs across a wide range of assumptions. Importantly, the robustness of these outcomes under sensitivity analysis indicates that the observed advantages are structurally embedded in the system design rather than contingent on favorable boundary choices or pricing assumptions.

These findings carry direct implications for engineering standards and infrastructure procurement frameworks. Current road subgrade specifications and material selection guidelines typically prioritize short-term strength criteria while treating environmental impacts as secondary or static

attributes. The results indicate that incorporating service-life-normalized environmental metrics and circular economy indicators into design codes and procurement thresholds would materially alter optimal stabilizer selection, particularly in regions where waste-derived materials are locally available. In this context, durability should be treated as an environmental performance parameter rather than solely a structural one.

From a policy standpoint, the results support the integration of carbon pricing, life-cycle costing, and circularity requirements into public infrastructure investment decisions. When such mechanisms are applied, waste-activated stabilization systems like WA+NaCl transition from being perceived as alternative or experimental options to being economically and environmentally rational defaults. This shift is especially relevant for developing regions, where rapid infrastructure expansion coincides with abundant biomass residues and constrained access to low-carbon industrial binders.

Overall, the mechanistic coupling of material chemistry, durability, and life-cycle outcomes demonstrated in this study provides a transferable framework for evaluating geotechnical stabilization strategies beyond mass-based comparisons. By explicitly linking engineering performance to lifetime environmental and societal impacts, the results offer a decision-relevant basis for advancing low-carbon, circular, and durable ground improvement practices.

4. Conclusions

This study demonstrates that wood ash activated with sodium chloride (WA+NaCl) constitutes a mechanistically superior and environmentally favorable alternative to conventional lime and cement binders for soil stabilization. By leveraging synergistic pozzolanic and chloride-activation reactions, WA+NaCl delivers enhanced mechanical durability, extending functional service life by

≥15 years relative to lime and cement systems. This durability-driven performance directly reduces material consumption, maintenance frequency, and lifetime emissions, highlighting the importance of integrating service-life normalization into life cycle assessments.

ISO-compliant cradle-to-grave LCA results reveal substantial environmental benefits, including an 85–90% reduction in embodied CO₂ emissions (5–15 kg CO₂-eq per tonne stabilized soil) compared to lime (80–100 kg) and cement (70–90 kg), supported by Nigerian-specific energy and transport modeling. Circular economy performance is also pronounced, with >95% waste valorization of wood ash, minimizing virgin material extraction, reducing non-climate externalities, and enhancing systemic sustainability. Moderate salinity risks from NaCl warrant site-specific management but do not outweigh the environmental and societal advantages observed.

Economically, WA+NaCl is competitive, achieving 10–30% savings in direct costs versus lime, with total societal costs (direct, climate, and non-climate) ranging from 28–51 USD/tonne—50–60% lower than lime and 40–50% lower than cement. Sensitivity analyses confirm that these benefits are robust across variations in carbon pricing, transport distances, and energy mixes.

These findings carry significant implications for infrastructure standards and procurement policies. Incorporating service-life-informed LCA metrics, circularity indicators, and monetized externalities into design codes and procurement frameworks could promote adoption of waste-derived stabilization systems, supporting decarbonization, resource efficiency, and circular economy transitions in developing regions.

Overall, WA+NaCl offers a scalable, net-positive solution for geotechnical applications, combining enhanced durability, reduced environmental impacts, economic competitiveness, and

circularity. Future work should focus on large-scale field validation, long-term leaching assessments, and integration with infrastructure design guidelines to enable widespread deployment.

Declaration

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflicts of Interest: The authors declare no conflicts of interest relevant to this work.

Ethics Approval: Not applicable.

Consent to Participate: Not applicable.

Consent for Publication: All authors consent to the publication of this manuscript.

Availability of Data and Materials: The datasets generated and analyzed during the current study are available on request.

Authors' Contributions

- Nura Yunusa conceptualized the study, conducted the LCA modeling, and drafted the manuscript.
- Mahmud Abubakar and Bashir Hamza Nauzo contributed to experimental design, data curation, and analysis.
- Olotu John, Hassan Tasi'u, and Lawn Garba Dan-Alhaji assisted with methodology, interpretation of results, and manuscript review.
- All authors read and approved the final manuscript.

References

Balagosa, J., Navea, I. J., Lee, M. J., Choo, Y. W., Kim, H.-S., & Kim, J.-M. (2024). Dynamic property growth of weathered granite soils stabilized with wood pellet fly ash based binders. *Soil Dynamics and Earthquake Engineering*, 180, Article 108627. <https://doi.org/10.1016/j.soildyn.2024.108627>

Díaz-López, J. L., Rosales, J., Agrela, F., Cabrera, M., & Cuenca-Moyano, G. M. (2024). Evaluation of geotechnical, mineralogical and environmental properties of clayey soil

- stabilized with different industrial by-products: A comparative study. *Construction and Building Materials*, 449, Article 138497. <https://doi.org/10.1016/j.conbuildmat.2024.138497>
- Ee, A. W. L., Chew, S. J., Khoo, H. H., Ng, A. T. S., & Kua, H. W. (2025). Circular economy for the building industry: Life cycle assessment of biochar-enhanced concrete. *Resources, Conservation and Recycling*, 223, Article 108537. <https://doi.org/10.1016/j.resconrec.2025.108537>
- Generowicz, A., Gronba-Chyła, A., Godula, P., Kulczycka, J., Lewandowska, A., Dorosz, A., Ciula, J., & Kwaśnicki, P. (2025). Assessment of the possibility of implementing a circular economy by environmental evaluating the life cycle of products derived from bulky municipal waste. *Sustainability*, 17(8), Article 3377. <https://doi.org/10.3390/su17083377>
- Habibi, A., Bamshad, O., Golzary, A., Buswell, R., & Osmani, M. (2024). Biases in life cycle assessment of circular concrete. *Renewable and Sustainable Energy Reviews*, 192, Article 114237. <https://doi.org/10.1016/j.rser.2023.114237>
- Mutel, C., Liao, X., Patouillard, L., Bare, J., Fantke, P., Frischknecht, R., Hauschild, M., Joliet, O., de Souza, D., Laurent, A., Pfister, S., & Verones, F. (2018). Overview and recommendations for regionalized life cycle impact assessment. *The International Journal of Life Cycle Assessment*, 24(5), 856–865. <https://doi.org/10.1007/s11367-018-1539-4>
- Nasiri, M., & Modarres, A. (2025). Stabilization of forest road subgrades with lime and wood ash: A sustainable approach to enhancing durability and reducing soil erosion under freeze–thaw cycles. *Results in Engineering*, 28, Article 108394. <https://doi.org/10.1016/j.rineng.2025.108394>

- Pavan, A. L. R., & Ometto, A. R. (2016). Regionalization of land use impact models for life cycle assessment: Recommendations for their use on the global scale and their applicability to Brazil. *Environmental Impact Assessment Review*, 60, 148–155. <https://doi.org/10.1016/j.eiar.2016.05.001>
- Yang, Y. (2016). Toward a more accurate regionalized life cycle inventory. *Journal of Cleaner Production*, 112, 308–315. <https://doi.org/10.1016/j.jclepro.2015.08.091>