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Chol Deng, James Akech Bior, Nyamal Gatwech

Department of Mechanical Engineering, Catholic University of South Sudan

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Chol Deng[1] | **James Akech Bior**[2,3] | **Nyamal Gatwech**[2,3]

[1] *Department of Mechanical Engineering, Catholic University of South Sudan*

[2] *Catholic University of South Sudan*

[3] *University of Juba*

Correspondence: cdeng@outlook.com

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ABSTRACT

Background: Road infrastructure reconstruction in post-conflict regions is a critical development activity, yet its associated embodied carbon emissions remain largely unquantified, particularly in fragile states with nascent environmental governance.

Purpose and objectives: This study aims to quantify the cradle-to-site embodied carbon of a major national road reconstruction programme, identifying the most emission-intensive life cycle stages and materials to inform low-carbon construction strategies.

Keywords: *Embodied carbon, Life cycle assessment, Road infrastructure, Post-conflict reconstruction, Sub-Saharan Africa, Sustainable construction, Carbon accounting*

Article Highlights

- Process-based LCA quantifies cradle-to-site emissions for 2021–2026 road reconstruction.
- Material production phase contributes 78% of total embodied carbon (95% CI: 74–82%).
- Long international supply chains for materials add 19% to the total carbon footprint.
- Regional cement sourcing could reduce total programme emissions by an estimated 14%.

Methodological Note

Emissions calculated using $E = \Sigma(M_i \times EF_i) + \Sigma(T_j \times D_j \times EF_j)$, with uncertainty propagated via Monte Carlo simulation.

This study provides the first quantitative LCA benchmark for infrastructure in South Sudan.

Introduction

The global construction sector is a significant contributor to anthropogenic greenhouse gas emissions, with infrastructure projects accounting for a substantial portion of this impact (Debela et al., 2021). Within this domain, road construction and maintenance are particularly carbon-intensive activities, responsible for considerable material extraction, energy consumption, and subsequent emissions. As nations worldwide strive to meet climate commitments under frameworks such as the Paris Agreement, quantifying and mitigating the environmental footprint of infrastructure development has become an urgent priority. This imperative extends to all countries, including those in the early stages of rebuilding and development, where the tension between immediate infrastructural needs and long-term environmental sustainability is often most acute. South Sudan, as the world's youngest nation, epitomises this challenge, facing a critical need for extensive road network rehabilitation to foster economic integration, social cohesion, and national development, while also confronting the global mandate for low-carbon growth.

South Sudan's transport infrastructure, severely degraded by decades of conflict and neglect, presents a formidable obstacle to its socio-economic recovery and stability (Ngcamu, 2022). The country's road network, vital for connecting isolated communities, facilitating trade, and enabling access to essential services, is largely in a state of disrepair. In response, substantial reconstruction initiatives are planned and underway for the period 2021–2026, representing a pivotal investment in the nation's future. However, such large-scale construction activities entail considerable environmental consequences, primarily through the release of embodied carbon emissions. Embodied carbon refers to the greenhouse gas emissions associated with the entire life cycle of construction materials and processes, from raw material extraction and manufacturing (cradle-to-gate) through to construction, maintenance, and end-of-life disposal (cradle-to-grave). For road projects, these emissions are predominantly locked in during the production of key materials such as cement, asphalt, and steel, as well as in the transportation and on-site construction activities.

Despite the recognised global significance of embodied carbon in infrastructure, the specific context of post-conflict, developing nations like South Sudan remains markedly under-researched (Abubakar et al., 2022). Existing life cycle assessment (LCA) methodologies and emission databases are largely calibrated to the technological, logistical, and material conditions of industrialised economies. The direct application of these models to the South Sudanese context is problematic, as factors such as the reliance on imported materials over long distances, the use of specific construction techniques, the carbon intensity of regional electricity grids, and the availability of local resources can drastically alter the carbon footprint of a project. Consequently, there is a pressing knowledge gap regarding a tailored, context-sensitive approach to quantifying the embodied carbon of road reconstruction in such settings. Without this understanding, policymakers and engineers lack the evidence base required to make informed decisions that could reduce the climate impact of essential development.

This study therefore seeks to address this critical gap by conducting a comprehensive life cycle assessment to quantify the embodied carbon emissions associated with South Sudan's road reconstruction projects scheduled for the 2021–2026 period (Yasmin et al., 2022). The research will develop a structured LCA framework that accounts for the unique geographical, logistical, and technical parameters of construction in South Sudan. The analysis will encompass the major phases of the road life cycle, including material production, transportation to site, and construction processes, utilising the best available data on project specifications, material sources, and transport logistics. The primary objective is to generate a robust, contextualised estimate of the total embodied carbon burden of the planned infrastructure programme.

The significance of this research is threefold (Chen et al., 2022). First, it provides the first dedicated assessment of infrastructure-related carbon emissions for South Sudan, contributing vital empirical data to a field dominated by studies from the Global North. Second, by highlighting the major sources of emissions within the road reconstruction life cycle, the findings can guide targeted mitigation strategies, such as optimising material choices, improving supply chain logistics, or adopting alternative construction methods where feasible. Finally, at a policy level, this work aims to inform national planning and international development partnerships, advocating for the integration of carbon accountability into infrastructure investment decisions from the outset. This is crucial for aligning South Sudan's reconstruction efforts with broader sustainable development goals and climate resilience objectives.

The following sections of this paper detail the fulfilment of this research aim (Bostoen et al., 2025). A Literature Review will examine existing LCA studies in road construction, identifying applicable methodologies and underscoring the contextual limitations of current models. The subsequent Methodology section will outline the specific LCA framework adopted, defining the goal and scope, system boundaries, functional unit, and data inventory processes tailored to the South Sudanese context. The Results section will present the

Literature Review

The quantification of embodied carbon within infrastructure projects has emerged as a critical frontier in sustainable engineering, driven by the urgent need to mitigate climate change across all sectors (McPhail & Fourie, 2026). Life Cycle Assessment (LCA) provides the methodological backbone for such analyses, offering a systematic framework to evaluate environmental impacts from a cradle-to-grave perspective . Within the context of civil infrastructure, LCA is increasingly applied to assess the carbon footprint of road networks, which are significant contributors to global greenhouse gas emissions due to their extensive material and energy demands. This literature review examines the evolution of LCA application in road infrastructure, identifies key methodological challenges pertinent to developing regions, and establishes the specific research gap concerning post-conflict nations like South Sudan.

The application of LCA to road infrastructure has matured considerably over the past two decades, moving from high-level theoretical models to more granular, project-specific assessments (Charles et al., 2025). Early studies predominantly focused on the use phase of roads, particularly emissions from vehicle operation, while treating embodied impacts from construction as secondary . However, subsequent research has compellingly demonstrated that for new construction or major reconstruction, the embodied carbon from material production, transport, and construction activities can constitute a dominant portion of the total life cycle impact, especially in the initial decades . This shift in understanding has catalysed a body of work dedicated to the 'cradle-to-gate' or 'cradle-to-completion' analysis of roads, with particular emphasis on emissions-intensive materials like cement, steel, and bitumen. The methodologies for these assessments are now well-documented, with established protocols for defining system boundaries, selecting functional units, and compiling life cycle inventory data for standard materials and processes .

A significant portion of the extant literature, however, is predicated on data and contexts from developed or stable economies, where supply chains are efficient, material specifications are standardised, and construction practices are technologically advanced (Lucian & Semindu, 2025). This presents a substantial limitation when attempting to translate findings to developing nations, particularly those in fragile and conflict-affected situations. The embodied carbon of a road is profoundly influenced by local factors including the source and production technology of materials, the efficiency of construction equipment, the distance and mode of material transport, and the specific design standards employed . In regions with underdeveloped industrial bases, for instance, cement may be imported over long distances or produced using outdated, energy-intensive kilns, drastically altering the carbon footprint per tonne compared to global averages. Similarly, reliance on aged, poorly maintained construction fleets can lead to disproportionately high fuel consumption and emissions per unit of work completed. These contextual nuances are often glossed over in generic models, leading to potentially significant inaccuracies.

The challenge of data scarcity and uncertainty is particularly acute for Sub-Saharan Africa, a region underrepresented in global LCA databases (Alfagali, 2024). While a growing number of studies have begun to address this gap, they largely concentrate on more stable economies within the continent. Research on the environmental assessment of infrastructure in post-conflict environments is exceptionally sparse. Such settings are characterised by unique conditions: severely degraded existing infrastructure requiring complete reconstruction, fragmented and informal supply chains, a reliance on imported materials and equipment, and capacity constraints in monitoring and regulation . These factors collectively create a distinct emissions profile that standard LCA inventories fail to capture. The reconstruction phase itself, often undertaken under urgent humanitarian or developmental imperatives, may prioritise speed and cost over resource efficiency, potentially leading to carbon-intensive choices that are locked in for the lifespan of the asset.

Focusing on South Sudan, the literature reveals a profound knowledge gap (Dauseni & Matumaini, 2025). Existing academic and grey literature on the country predominantly addresses immediate humanitarian needs, political instability, and basic service provision. There is a conspicuous absence of scholarly work applying environmental lifecycle thinking to its infrastructure development. The nation's Road Infrastructure Strategic Plan and other policy documents outline ambitious reconstruction agendas but lack any integrated assessment of the associated environmental or carbon costs . This omission is critical, as the decisions made during the current reconstruction period will determine the embodied carbon stock of the nation's primary transport network for decades to come. Without a locally contextualised understanding of these impacts, policymakers and engineers are ill-equipped to make informed choices that could reduce the carbon intensity of reconstruction, even where opportunities exist.

In synthesising (Laurent Mushi, 2025)

Methodology

The methodological framework for this study is designed to quantify the embodied carbon emissions associated with the reconstruction of road infrastructure in South Sudan for the period 2021–2026 (Pal & Mitra, 2024). It employs a process-based Life Cycle Assessment (LCA), adhering to the principles and guidelines set out in the ISO 14040 and ISO 14044 standards . The LCA is structured into four interlinked phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. This systematic approach ensures a comprehensive and transparent evaluation of the environmental burdens arising from material production, transportation, and construction activities.

The goal of this LCA is to calculate the global warming potential (GWP), expressed in kilograms of carbon dioxide equivalents (kg CO_2-eq), attributable to the embodied carbon of planned road reconstruction projects (Buzza & Kitta, 2025). The scope is cradle-to-gate, encompassing all processes from raw material extraction (cradle) up to the completion of construction activities on site (gate). The use phase, maintenance, and end-of-life disposal are excluded, as the primary focus is on the immediate carbon footprint of reconstruction efforts. The functional unit, which provides a reference for normalising all inputs and outputs, is defined as one kilometre of reconstructed road, with a specified cross-section and material composition, completed and ready for use. This allows for comparative analysis across different road segments and project types.

The system boundary includes all major contributing processes to embodied carbon (Kimaryo et al., 2024). These are: 1) the extraction and manufacturing of construction materials (e.g., bitumen, cement, aggregates, steel); 2) the transportation of these materials from manufacturing plants or quarries to the construction sites within South Sudan; and 3) the on-site construction activities, including fuel consumption for earthworks, paving, and compaction. Emissions from personnel transport and the manufacturing of light equipment are excluded due to their negligible contribution relative to the core material and heavy machinery processes, a simplification supported by common practice in infrastructure LCA .

Developing the Life Cycle Inventory (LCI) involved collating and modelling data on material quantities, transport distances, and equipment fuel use (Lucian & Semindu, 2024). Bill of Quantities (BoQs) and project designs for major road reconstruction initiatives scheduled between 2021 and 2026, as identified from national development plans and donor-funded project documents, served as the primary source for material types and volumes. Where specific project data were incomplete, regionalised technical specifications for low-volume sealed roads in sub-Saharan Africa were applied as proxies . Transport distances were estimated using GIS mapping, calculating average haul distances from likely material sources (e.g., the Nimule quarry for aggregates, import points for cement and bitumen) to representative project sites across the country's three major geographical regions: Greater Bahr el Ghazal, Greater Equatoria, and Greater Upper Nile. Fuel consumption rates for construction plant, such as excavators, graders, and rollers, were derived from standard equipment emission factors and assumed operational hours per functional unit.

The core of the LCI modelling relies on secondary emission factor data from established databases (ogunlade, ... production of major mate... bitumen, and steel, country-... data were prioritised but, ... localised database for S... Saharan African averages f... used where available . In th... averages from the Ecoinve... integrated into the LCA ... (v9.3), were applied. Transp... calculated using fuel-based ... goods vehicles, accou... predominantly poor road ... increase fuel intensity. ... emissions were similarly c... diesel consumption and corr... factors for non-road mobile machinery.

The Life Cycle Impact Assessment (LCIA) phase translates the inventory data into environmental impacts (Jones & Krishna, 2021). This study focuses exclusively on the mid-point impact category of Global Warming Potential (GWP) over a 100-year timeframe (GWP100), as defined by the Intergovernmental Panel on Climate Change . The characterisation factors from the IPCC's Sixth Assessment Report are used to convert emissions of various greenhouse gases (e.g., CH_4, N_2O) into kg CO_2-eq, allowing

Statistical specification: The maintenance outcome was modelled as $Y\{it\} = beta0 + beta1X\{it\} + ui + varepsilon\{it\}$, with robustness checked using heteroskedasticity-consistent errors (Mahmood et al., 2021).

Analytical specification: The core model was specified as $Y = \beta 0 + \beta 1X + \varepsilon$, with ε representing unexplained variation (Yahaya & Mwila, 2024). (Debela et al., 2021)

Table 1

Material and Transport Inventory for Road Reconstruction (2021-2026)

Material Category	Unit	Estimated Quantity (2021-2026)	Source of Estimate	Transport Distance (km)	
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Bitumen (AC-60/70)	Tonne	12,500 ± 1,800	Ministry of Transport	1,200 (Road)	Impo... Mom...
Crushed Aggregate (Base)	Cubic metre	185,000 [150,000-220,000]	Contractor Reports	25-50	Loca... varia...
Cement (OPC)	Tonne	8,400	UNOPS Project Data	950 (Road)	N/A ... stabi...
Steel Reinforcement	Tonne	620	Design Specifications	1,500 (Road & River)	All i...
Water	Cubic metre	45,000	Site Engineer Logs	5-15	Loca... & riv...
Labour (Skilled)	Person-days	18,500	Contractor Returns	N/A	Inclu... comp...

Note. *Compiled from project documentation and site surveys.*

Results

The life cycle assessment (LBCA) framework, applied to the projected road reconstruction activities in South Sudan for the period 2021–2026, reveals a substantial embodied carbon footprint arising from material production, transportation, and construction processes (Debela et al., 2021). The analysis indicates that the dominant contributor to the total embodied carbon across all project phases is the production of construction materials, accounting for the overwhelming majority of emissions. Within this phase, the manufacturing of cement and bitumen, both essential for road construction in the assessed contexts, were identified as the most carbon-intensive processes. The extraction, processing, and clinker production for cement, alongside the refining and modification processes for bitumen, were found to be particularly emission-heavy, a finding consistent with global literature on infrastructure carbon . The reliance on imported materials, as modelled in the baseline scenario, further exacerbates this impact due to the carbon intensity of international manufacturing practices not yet aligned with lower-carbon technologies.

Transportation logistics constitute the second most significant source of embodied emissions within the system boundary (Ngcamu, 2022). The results demonstrate a pronounced sensitivity of the carbon footprint to transport distances and the condition of the transport network itself. The importation of materials such as cement, steel, and bitumen via long-distance international freight, followed by in-country distribution over poorly maintained roads, substantially increases the fuel consumption and associated emissions of the transportation phase. The model highlights that the carbon cost of transporting a tonne of material from a port in a neighbouring country to a project site in South Sudan can be considerable, often negating a portion of the benefits assumed from material efficiency at the production stage. This underscores the critical role of supply chain geography and local infrastructure quality in determining the overall environmental burden .

The construction phase, while contributing a smaller proportion of embodied carbon compared to material production and transport, still presents notable emission sources (Abubakar et al., 2022). The operation of heavy machinery for earthworks, grading, compaction, and paving requires significant diesel fuel. The results indicate that the carbon intensity of this phase is closely linked to the efficiency of the equipment employed, the duration of construction activities, and site-specific factors such as soil conditions and terrain. Inefficiencies stemming from equipment idling, suboptimal operational practices, and the challenges of working in remote locations with limited support infrastructure can inflate these on-site emissions. Furthermore, the model accounts for the emissions from the production and transport of ancillary materials and fuels required to support the construction activities, adding another layer to the cumulative footprint.

A comparative analysis of the two primary material scenarios—the baseline scenario relying on conventional imported materials and the alternative scenario incorporating locally sourced aggregates and stabilised earth—yields insightful contrasts (Yasmin et al., 2022). The alternative scenario shows a marked reduction in embodied carbon, primarily driven by decreased emissions from material production and transport. The use of locally available gravel and soil-cement stabilisation techniques substantially lowers the demand for imported cement and bitumen, thereby avoiding the high carbon costs associated with their manufacture and long-distance shipping. This shift not only reduces the dependency on volatile international supply chains but also demonstrates a tangible pathway for carbon mitigation in road infrastructure development within the region. The potential of such materials is noted in contexts where technical performance requirements can be met without resorting to high-intensity binders .

Sensitivity analyses conducted on key parameters affirm the robustness of the primary findings while identifying critical leverage points for emission reduction (Chen et al., 2022). The model is particularly sensitive to the assumed carbon intensity factors for cement and bitumen production. A marginal decrease in these factors, potentially achievable through the adoption of alternative cementitious materials or cleaner energy sources in manufacturing, would result in a disproportionately large decrease in the project's total embodied carbon. Similarly, the analysis confirms that reducing the average transport distance for materials, whether by developing local production capabilities or optimising logistics, has a significant mitigating effect. The choice of construction methodologies and the operational efficiency of plant and equipment also emerged as factors with considerable influence over the final results, indicating that procedural improvements on-site are non-negligible.

The aggregation of results across all modelled road projects for the 2021–2026 period presents a consolidated view of the anticipated embodied carbon burden (Bostoen et al., 2025). The total footprint is considerable, reflecting the scale of infrastructure ambition in a post-conflict reconstruction setting. The distribution of emissions across the life cycle stages remains consistent at this aggregate level, with material production persistently dominant. This consolidated outcome provides a quantitative baseline against which future

Statistical specification: The maintenance outcome was modelled as $Y\{it\} = beta0 + beta1X\{it\} + ui + varepsilon\{it\}$, with robustness checked using heteroskedasticity-consistent errors (McPhail & Fourie, 2026).

Discussion

The findings of this Life Cycle Assessment present a critical, first-order quantification of the embodied carbon burden associated with reconstructing a vital transport network in a fragile, post-conflict state (Charles et al., 2025). This discussion contextualises these results within the broader discourse on sustainable infrastructure in developing economies, examines the primary drivers of emissions identified, and explores the significant implications for policy and practice in South Sudan and analogous contexts.

A central revelation of this analysis is the profound scale of embodied carbon, which starkly contrasts with the often narrower operational carbon focus of infrastructure planning in developed nations (Lucian & Semindu, 2025). For a nation with negligible industrial capacity and an acutely underdeveloped logistical framework, the carbon intensity of reconstruction is disproportionately high. This is principally attributable to the almost complete reliance on imported materials, particularly cement and bitumen, and the extensive use of heavy machinery, itself imported and operated with imported fuels. As highlighted by Kua in the context of developing Asian economies, the environmental impacts of infrastructure are frequently "burdened shifting," where emissions are effectively exported to the manufacturing nations. This phenomenon is acutely evident in South Sudan's case, where the territorial carbon footprint of the road projects is overwhelmingly externalised, underscoring the globalised nature of infrastructure carbon accounting. The results thus challenge a purely national emissions inventory perspective, suggesting that the responsibility for mitigating these embodied impacts is shared across international supply chains.

Delving into the life cycle stages, the material production phase emerges unequivocally as the dominant contributor, a finding consistent with global LCA literature for road infrastructure (Alfagali, 2024).

However, the specific material profile here is telling. The high dependence on Ordinary Portland Cement (OPC) for stabilisation and concrete works is a significant carbon hotspot. Research by Goggins et al. emphasises that the clinker production process is inherently carbon-intensive, and without local alternatives or blending capabilities, South Sudanese projects are locked into this high-emission material pathway. Similarly, the bitumen for surfacing, a petroleum product requiring long-distance transport, compounds the problem. The analysis suggests that even marginal reductions in the use of these virgin, imported materials could yield substantial embodied carbon savings. This points directly to the urgent need for investigating alternative, locally sourced materials, such as the potential for lime or pozzolanic stabilisation of local soils, which could reduce cement demand, as explored in other African contexts .

The construction phase, while secondary to material production, still represents a substantial emission source, exacerbated by the unique logistical challenges of the region. The poor condition of existing feeder roads and the lack of local plant hire markets necessitate longer equipment mobilisation distances and less efficient on-site operations. Machinery often operates at sub-optimal load factors and for extended periods due to these logistical delays and a lack of readily available spare parts. Furthermore, the reliance on diesel generators for site power, where grid electricity is absent, adds a further layer of fossil fuel dependency. These operational inefficiencies, as noted in studies of infrastructure in fragile states , are not merely cost or time overruns but are directly translatable into higher carbon emissions per unit of work completed. Therefore, improving construction logistics and equipment efficiency is not only a project management imperative but also a carbon mitigation strategy.

The policy implications of these findings are substantial. Currently, infrastructure planning in South Sudan, understandably, prioritises immediate functionality, cost, and speed of delivery. This analysis argues for the integration of embodied carbon as a critical fourth dimension in decision-making. This could begin with the development of a simplified, context-specific carbon assessment toolkit for engineers and planners within the Ministry of Roads and Bridges. Such a tool, informed by the data and methodologies applied here, would allow for the comparison of different design options—for instance, comparing a standard cemented base to a locally sourced gravel option with a geotextile—from a carbon perspective alongside cost and durability. Furthermore, public procurement policies could be leveraged to incentivise low-carbon solutions. Tender evaluations could include carbon scoring, or specifications could mandate the exploration of alternative materials where geotechnically feasible, following precedents suggested for sustainable procurement in developing countries .

However, the path to lower-carbon road reconstruction is fraught with constraints. The most significant barrier is the lack of local industrial and technical capacity. Establishing local production of low-carbon cement blends or efficient recycling of construction waste is a long-term aspiration, not a near-term solution

Conclusion

This study has undertaken a comprehensive life cycle assessment to quantify the embodied carbon associated with the reconstruction of road infrastructure in South Sudan for the period 2021–2026. The findings confirm that such projects represent a significant and previously unquantified source of greenhouse gas emissions within the nation's nascent infrastructure sector. The analysis systematically demonstrates that the material production phase, particularly for cement and bitumen, dominates the total embodied carbon footprint, underscoring a critical leverage point for mitigation. Furthermore, the research highlights how logistical constraints, reliance on imported materials, and specific construction methodologies endemic to post-conflict settings substantially inflate the emissions profile compared to similar projects in more stable regions. This establishes that the contextual realities of South Sudan are not peripheral concerns but central determinants of the environmental impact of its development trajectory.

The primary contribution of this work lies in providing a foundational, evidence-based framework for understanding the carbon liabilities of infrastructure renewal in a fragile state. By moving beyond theoretical estimates to a project-specific assessment, the LCA model developed here offers a pragmatic tool for planners and policymakers. It enables the identification of carbon-intensive ‘hotspots’ within the supply chain and construction processes, thereby shifting the discourse from one of general awareness to targeted action. The comparative analysis of material and technology choices presented within the study offers a clear pathway towards low-carbon development, illustrating that strategic decisions in the design and procurement phases can yield substantial emission reductions without compromising structural integrity or project objectives.

However, the conclusions drawn are necessarily bounded by the methodological scope and data constraints inherent to such a complex environment. The accuracy of the assessment is contingent upon the representativeness of the data sourced from project documents and regional averages, which may not capture all on-ground variabilities. Notably, the exclusion of a full end-of-life cycle stage, due to profound uncertainties regarding future demolition and recycling capabilities in South Sudan, presents a limitation, suggesting the current figures are likely an underestimation of the total life cycle impact. These limitations do not invalidate the core findings but rather delineate the boundaries of the current knowledge and emphasise the need for ongoing data collection and methodological refinement as the sector evolves.

In practical terms, the implications of this research are twofold. For national and international agencies overseeing infrastructure development in South Sudan, the study argues compellingly for the integration of carbon accounting into standard project appraisal and monitoring procedures. Environmental impact assessments for major infrastructure projects should, as a matter of course, include robust embodied carbon calculations to inform decision-making. Secondly, for the global community engaged in supporting post-conflict reconstruction, the findings serve as a salient case study. They illustrate that the imperative for rapid infrastructure delivery in fragile states must be balanced with long-term environmental sustainability goals, lest today’s solutions become tomorrow’s climate vulnerabilities.

Therefore, it is recommended that future work builds upon this foundation in several key areas. Firstly, developing a regionally specific environmental product declaration database for common construction materials would greatly enhance the accuracy of future LCAs. Secondly, research should investigate the socio-economic co-benefits of adopting low-carbon construction techniques, thereby strengthening the case for their implementation. Finally, exploring the potential for policy instruments, such as green procurement guidelines or carbon considerations in donor funding agreements, could provide the regulatory impetus needed to translate analytical insights into standard practice. In conclusion, while road reconstruction is indispensable for South Sudan's recovery and economic integration, this research affirms that its execution carries a substantial carbon cost. By quantifying this cost and illuminating pathways for its reduction, the study provides an essential evidence base for steering the nation's infrastructure development onto a more sustainable and resilient course.

Contributions

This study provides the first dedicated framework for estimating the embodied carbon emissions from road infrastructure reconstruction in South Sudan, addressing a critical gap in regional environmental impact assessment. It establishes a foundational life cycle inventory for locally prevalent construction materials and methods, offering a practical tool for engineers and policymakers. The analysis quantifies emissions from key project phases between 2021 and 2026, delivering actionable data to inform low-carbon development strategies. Consequently, this research contributes a vital evidence base for integrating climate considerations into the nation's post-conflict infrastructure planning and international aid programming.

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