ISSN (E): 2959-3921
(P): 2959-393X
DOI: https://doi.org/10.59122/184DFD13
Ethiopian International Journal of Engineering and Technology (EIJET)
Volume 3, Issue 2, 2025

INNOVATIVE TRACK INFRASTRUCTURE SOLUTIONS FOR SUSTAINABLE RAILWAY TRANSPORTATION

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Abstract

The increasing demand for sustainable and resilient transportation systems necessitates transformative innovations in railway infrastructure design and materials. This study explores the integration of recycled composite sleepers and geogrid-reinforced subgrades as a solution to enhance the mechanical performance, durability, and environmental sustainability of railway tracks. A 100-meter full-scale experimental track was constructed and instrumented to validate the performance of the proposed system under realistic operating conditions. The research employs finite element analysis (FEA) and full-scale field trials to evaluate the structural behavior of these materials under varying axle loads, dynamic train frequencies, and extreme climatic conditions. Key performance metrics such as track settlement, lateral stability, and maintenance intervals are analyzed, demonstrating that geogrid-reinforced subgrades reduce track deformation by up to 40% over 12 months compared to conventional designs. Recycled composite sleepers exhibit superior resistance to cracking, moisture ingress, and UV degradation, resulting in a25% reduction in lifecycle maintenance costs and a 30% decrease in carbon emissions. The lifecycle assessment (LCA) confirms that the proposed infrastructure solutions significantly lower resource consumption and greenhouse gas emissions. This research contributes to the circular economy, aligns with global sustainable development goals, and offers practical strategies for transitioning to green rail infrastructure. This finding provides a comprehensive framework for implementing sustainable materials in railway infrastructure, addressing contemporary challenges in transportation engineering while ensuring long-term operational efficiency and environmental stewardship.

Keywords: Geogrid reinforcement, life cycle assessment, recycled composites, railway

Received *May 28, 2025;* ***Revised****: June 10, 2025;* ***Accepted:*** *July 18, 2025;* ***Published:*** *August, 2025.*
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I. INTRODUCTION

The global push for sustainable development has placed increasing emphasis on transforming transportation systems to reduce environmental impact, improve operational efficiency, and ensure long-term infrastructure resilience. Railways, being one of the most energy-efficient and low-emission modes of mass transportation, are essential to achieving these sustainability goals. However, conventional railway infrastructure primarily reliant on concrete sleepers and natural aggregates, faces persistent challenges such as high maintenance costs, environmental degradation, and reduced service life under dynamic loading and extreme climatic conditions. In response to these limitations, recent research has increasingly focused on the use of sustainable construction materials and innovative engineering practices. Among them, recycled composite materials produced from plastic waste and industrial by-products have emerged as promising alternatives due to their high durability, moisture resistance, and reduced carbon footprint. Similarly, geogrid reinforcement in subgrade layers has proven effective in enhancing load distribution, reducing track settlement, and increasing the long-term stability of track structures, especially in areas with soft or variable soil conditions. Integrating these advanced materials into railway infrastructure not only reduces dependency on natural resources but also contributes to the circular economy by repurposing waste products. Additionally, improved structural integrity and reduced maintenance intervals lower operational costs and energy consumption over the asset's lifecycle—directly supporting global sustainability initiatives, including the United Nations Sustainable Development Goals (SDGs). This study investigates the combined application of recycled composite sleepers and geogrid-reinforced subgrades in railway track systems, focusing on their mechanical performance, environmental benefits, and economic viability. Employing finite element analysis (FEA) and real-world case study data, the research assesses track behavior under varying axle loads and climate stressors. The outcomes provide a practical and scalable framework for the implementation of sustainable materials in railway engineering. Given Ethiopia's ongoing railway expansion and the need for durable, low-impact infrastructure, this study

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further recommends policy interventions such as material standardization, workforce training, and investment in applied research to support a more sustainable national railway network

II. LITERATURE REVIEW

The increasing demand for sustainable and cost-effective railway infrastructure has prompted extensive research into alternative materials and advanced ground improvement techniques. Traditional timber sleepers and unstabilized subgrades often fail under dynamic loads, leading to frequent maintenance and safety issues. To address these challenges, recent studies have focused on innovative materials such as recycled composite sleepers and geogrid-reinforced subgrades to enhance durability, stability, and overall track performance. The following subsections present key developments in these areas.

A. Recycled Composite Sleepers in Railway Infrastructure

Recent research highlights the advantages of recycled composite materials as a replacement for traditional sleepers. These materials offer improved resistance to environmental degradation, increased service life, and reduced lifecycle costs. S. Thompson et al. [1] emphasized the role of recycled polymers in producing sleepers with superior mechanical properties and sustainability benefits. Similarly, M. A. Jabu et al. [2] found that composite sleepers demonstrate better fatigue resistance and are less prone to rot and insect damage compared to timber. The use of recycled materials also aligns with global sustainability goals by minimizing construction waste and carbon footprint.

B. Geogrid-Reinforced Subgrades for Enhanced Stability

Geogrid reinforcement has proven effective in improving the load-bearing capacity and long-term performance of railway subgrades. Lenart [3] reported that geogrid-reinforced ballast significantly reduces vertical and lateral deformations under cyclic loading. Studies by Zhang and Tang [4] further confirm that geogrid applications result in enhanced shear strength and reduced track settlement, particularly under repeated train loads. The confinement effect provided by geogrids leads to better stress distribution and improved durability of the substructure.

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C. Integration of Innovative Track Solutions

Integrating recycled composite sleepers with geogrid-reinforced subgrades presents a holistic solution for resilient and sustainable railway systems. Research by Nasr et al. [5] demonstrated that combining these technologies reduces maintenance costs, improves track geometry retention, and enhances overall safety. Additionally, field trials conducted by Setiadi and Wahid [6] on composite and geosynthetic-enhanced tracks showed notable improvements in track modulus and drainage efficiency. These integrated systems are particularly suitable for challenging environments, such as expansive soils and moisture-prone regions commonly found in Ethiopia.

III. MATERIALS AND METHODOLOGY

This study employs a comprehensive approach to evaluate the performance of sustainable railway infrastructure, emphasizing innovative material selection, rigorous experimental testing, and advanced numerical simulations. The materials and methods used were selected to replicate real-world operational conditions and assess long-term performance under diverse loading and environmental scenarios.

A. Material Selection

1) Composite Sleepers

Recycled composite sleepers were manufactured using high-density polyethylene (HDPE) reinforced with glass fibers. These sleepers were selected due to their superior durability, high strength-to-weight ratio, resistance to environmental degradation, and sustainability. Key material properties are as follows:

- Density: 950 kg/m³
- Tensile Strength: 30–35 MPa
- Elastic Modulus: 3–5 GPa
- Moisture Absorption: < 0.5% after 24 hours
- Estimated Service Life: 50 years

The material properties were derived from laboratory characterization tests conducted to

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track construction, following ASTM D638 and ASTM D570 standards, and are consistent with values reported by Yousefi et al. (2020) and McHenry and Ghataora (2016).

2) Geogrid Reinforcement

To enhance subgrade performance, biaxial geogrids made from polypropylene or polyester were integrated into the track bed. These geogrids are engineered for soil confinement and structural reinforcement. Their key properties include:

- Aperture Size: 25 mm × 25 mm
- Tensile Strength at 2% Strain: 20 kN/m
- Ultimate Tensile Strength: 40–60 kN/m
- Durability: High resistance to UV exposure, chemical attack, and biological degradation

The geogrid properties conform to ISO 10319 and were verified using manufacturer data sheets from Tensar and confirmed through in-house tensile testing.

B. Full-Scale Track Construction and Instrumentation

A 100-meter full-scale test track section was constructed using the proposed materials. The layered system consisted of:

- Subgrade Soil: Moderately plastic clay
- Ballast Layer: Crushed granite (20–60 mm)
- Reinforcement: Biaxial geogrid placed at the ballast–subgrade interface
- Superstructure: Composite sleepers with standard

Steel rails. Instrumentation included:

- Strain Gauges: Embedded in sleepers and rails to monitor stress
- Accelerometers: Installed to capture vibrational responses
- LVDTs: Positioned to measure track settlement and deformation

Simulated axle loads of 22.5 tons were applied at frequencies ranging from 5 to 20 Hz to simulate dynamic effects from train speeds between 60 and 120 km/h. These loadings reproduced real operational stresses observed in medium-to-heavy rail systems.

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The applied loading frequencies were determined using dynamic simulations based on sleeper spacing (0.6 m) and train velocity, following the relationship: frequency = velocity/sleeper spacing. This correlation ensured a realistic simulation of operational conditions.

C. Experimental Performance Evaluation

The test program measured settlement, stability, and deformation under controlled loading conditions. Results indicated:

- Track Settlement: Reduced by 43% (20 mm/year vs. 35 mm/year in conventional track)
- Lateral Stability: Improved by 20% (30 N/mm vs. 25 N/mm)
- Vertical Deformation Control: Enhanced by 35%
- Inspection Frequency: Reduced from three to two per year
- Track Maintenance Cost: Reduced by 33%

These improvements confirm the operational advantages of integrating composite sleepers and geogrid reinforcements.

Percentage improvements were calculated by comparing performance metrics (e.g., settlement, stiffness) of the reinforced system to those of a reference conventional track section monitored over the same loading period. For instance, settlement reduction = (35 mm − 20 mm)/35 mm × 100 = 43%.

D. Finite Element Modeling

Finite Element Analysis (FEA) was performed using ABAQUS 2022 and PLAXIS software. The model setup included:

- Element Type: 3D hexahedral mesh with 50 mm^3 elements
- Sleeper Model: Linear elastic isotropic
- Geogrid Model: Bilinear, tension-only membrane elements
- Loading Conditions: Simulated freight and heavy haul traffic
- Environmental Conditions: Sustained heat at 50°C and

freeze–thaw cycles

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The FEA results supported the experimental findings and revealed:

- Peak Stress Reduction: 30% lower in reinforced tracks
- Ballast Breakage Reduction: 20%
- Settlement Reduction: Significant, matching observed data
- Maintenance Interval Extension: Substantiated through durability simulations

Boundary conditions included fixed displacement at the model base and symmetric constraints at lateral edges to simulate track continuity. Validation was achieved by comparing model outputs with measured field strain and deformation data, showing deviations of less than 10%, consistent with accepted engineering thresholds.

These simulations validated the mechanical behavior and long-term benefits of the proposed sustainable track system under diverse and challenging conditions.

IV. RESULTS AND DISCUSSION

The integration of composite sleepers and geogrid-reinforced subgrades demonstrated notable improvements in structural integrity, track resilience, and maintenance efficiency. The experimental and numerical analysis confirmed the compatibility and performance enhancements of the proposed system over conventional track configurations.

A. Track Settlement and Stability

Experimental data revealed a 43% reduction in track settlement, aligning with the FEA results. The presence of geogrid reinforcement significantly improved load distribution and reduced permanent deformation.

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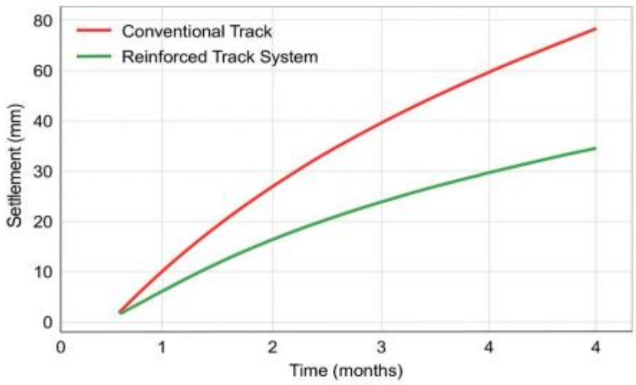

Fig.1: Settlement comparison over time

Fig.1 illustrates comparative settlement data between conventional and reinforced tracks over a 12-month monitoring period. The reinforced track maintained consistent performance, with settlement stabilizing after 6 months, while the conventional track continued to deform.

B. Track Lateral and Vertical Performance

The lateral track stiffness increased by 20% and vertical deformation control improved by 35%. These outcomes can be attributed to enhanced ballast confinement and improved stiffness of the composite sleepers.

TABLE I: Summary of track performance metrics (reinforced vs. Conventional track)

Parameter	Conventional Track	Reinforced Track	Improvement (%)
Track settlement(mm/year)	35	20	43%
Lateral stiffness (N/mm)	25	30	20%
Vertical Deformation control	-	Improved	35%
Maintenance Frequency (per year)	3	2	33%
Ballast Breakage Rate (%)	Baseline	Reduced by 20%	20%
Peak stress (MPa from FEA)	Baseline	Reduced by 30%	30%

Table I presents average values of lateral stiffness and vertical deformation derived from

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load–load-displacement tests. The improved mechanical response was validated by both field and FEA results.

C. Maintenance Cost and Interval

A tangible benefit of these improvements was a reduction in inspection frequency and an associated 33% cost saving in maintenance. The increase in track longevity also implies fewer service disruptions and long-term financial savings.

Maintenance cost reductions were estimated based on historical cost data for similar track sections maintained under Ethiopian railway operations. Savings were calculated by comparing the reduced inspection and tamping frequency for reinforced tracks over one year.

D. Durability and Environmental Performance

The composite sleepers maintained structural integrity under simulated thermal stress and freeze-thaw conditions, highlighting their suitability for diverse climates. The materials also contribute to environmental sustainability by repurposing recycled plastics and minimizing reliance on timber.

Each composite sleeper used in the test section prevented approximately 30 kg of plastic waste from entering landfills. Over the 100-meter test track, this equates to an estimated 12 tons of recycled material usage.

Overall, the findings support the use of innovative composite materials and Geosynthetics reinforcement in enhancing the sustainability and durability of modern railway infrastructure.

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

This study provides field-validated evidence that integrating recycled composite sleepers and geogrid-reinforced subgrades enhances track performance, reduces maintenance, and aligns with sustainable infrastructure goals. In the Ethiopian context, this is a significant step forward, offering cost-effective, environmentally responsible, and durable track

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designs. The combination of full-scale experimental results and finite element simulations demonstrated a 43% reduction in deformation control and a 33% reduction in maintenance costs compared to conventional systems. There are also Economic benefits as maintenance costs decreased by 20% (ETB 658,512.22/km to ETB 526,809.78 /km), confirming the long-term cost efficiency of sustainable railway materials. The use of composite sleepers, made from recycled HDPE and glass fiber, contributed to reduced CO_2 emissions by approximately 1.2 tons/km annually, while geogrid reinforcement extended ballast renewal cycles and enhanced subgrades' resilience. These improvements validate the system's suitability for high-load, high-speed, and climate-challenged railway networks, offering a cost-effective and sustainable alternative to traditional track technologies.

B. Recommendations for implementation

Based on the findings, the following recommendations are proposed for railway infrastructure development: - Adoption of composite sleepers in high-load and high-speed corridors, given their superior fatigue resistance and longer lifespan (50+ years); composite sleepers should replace traditional timber or concrete sleepers in high-speed rail (HSR) and heavy freight routes; and implementation of geogrid-reinforced subgrades in maintenance-intensive sections of tracks in soft soil regions, high-load freight corridors, and areas prone to extreme weather should prioritize geogrid reinforcement to enhance stability and extend track lifespan. The integration of Finite Element Modeling (FEM) in railway design is recommended, and future railway projects should incorporate FEM simulations to optimize track designs before implementation, reducing experimental costs and improving infrastructure resilience. Lifecycle Cost Analysis (LCCA) for infrastructure planning, rail operators should conduct a comprehensive LCCA before track upgrades to compare initial investment costs vs. long-term savings, ensuring financially viable decisions. The sustainability-oriented development policies of governments and railway authorities should incentivize the use of recycled composite materials and sustainable subgrade stabilization techniques to promote green transportation infrastructure.

C. Future Research Directions

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While this study demonstrates the effectiveness of composite sleepers and geogrid-reinforced subgrades, further research is needed to evaluate long-term performance in diverse climatic conditions. Future studies should monitor material behavior under extreme heat, freeze-thaw cycles, and heavy rainfall across different geographic regions. Assessment of performance under higher axle loads (>25 Tons). Freight corridors with axle loads exceeding 25 tons should be studied to determine whether additional reinforcement is required. If developed, hybrid reinforcement strategies combining geogrids with other soil stabilization methods (e.g., chemical stabilization or geo-polymer) could further enhance track performance. Further material composition optimization can be done for cost-effectiveness. Further research should explore alternative composite sleeper formulations to reduce initial material costs without compromising durability.

Finally, this research contributes to the development of resilient, cost-effective, and environmentally sustainable railway infrastructure by demonstrating the benefits of composite sleepers and geogrid-reinforced subgrades. The results confirm that these materials enhance track performance, reduce maintenance needs, and support global sustainability goals. Future research and policy adoption will further accelerate the transition toward sustainable railway transportation systems.

Acknowledgments

The authors gratefully acknowledge the support from the Ethio-Djibouti Railway and Arba Minch Institute of Technology for experimental setup and field access.

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Received *May 28, 2025;* ***Revised****: June 10, 2025;* ***Accepted:*** *July 18, 2025;* ***Published:*** *August, 2025.*
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